MOSSGAS

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16 September 1999

Program Manager
Energy Policy Act and Alternative Fuels,
Office of Transportation Technologies,
U.S. Department of Energy,
1000 Independence Avenue, SW
Washington, D.C. 20585

Attention: Kenneth Katz

RE: MOSSGAS RFD DIESEL FUELS AS ALTERNATIVE FUELS

Dear Mr. Katz

Please find our petition to have our three diesel fuels designated as "alternative fuels" as defined in the U.S. Energy Policy Act (EPACT) of 1992.

It is our opinion that our reformulated "gas to liquid" diesel fuels fully complies the EPACT requirements.

We have included all the documents cited in our petition for your easy reference.

Could you please acknowledge receipt of this petition and advise a timetable for the process.

We look forward to hearing from you.

Should you require any further information please contact Cyril Knottenbelt at:

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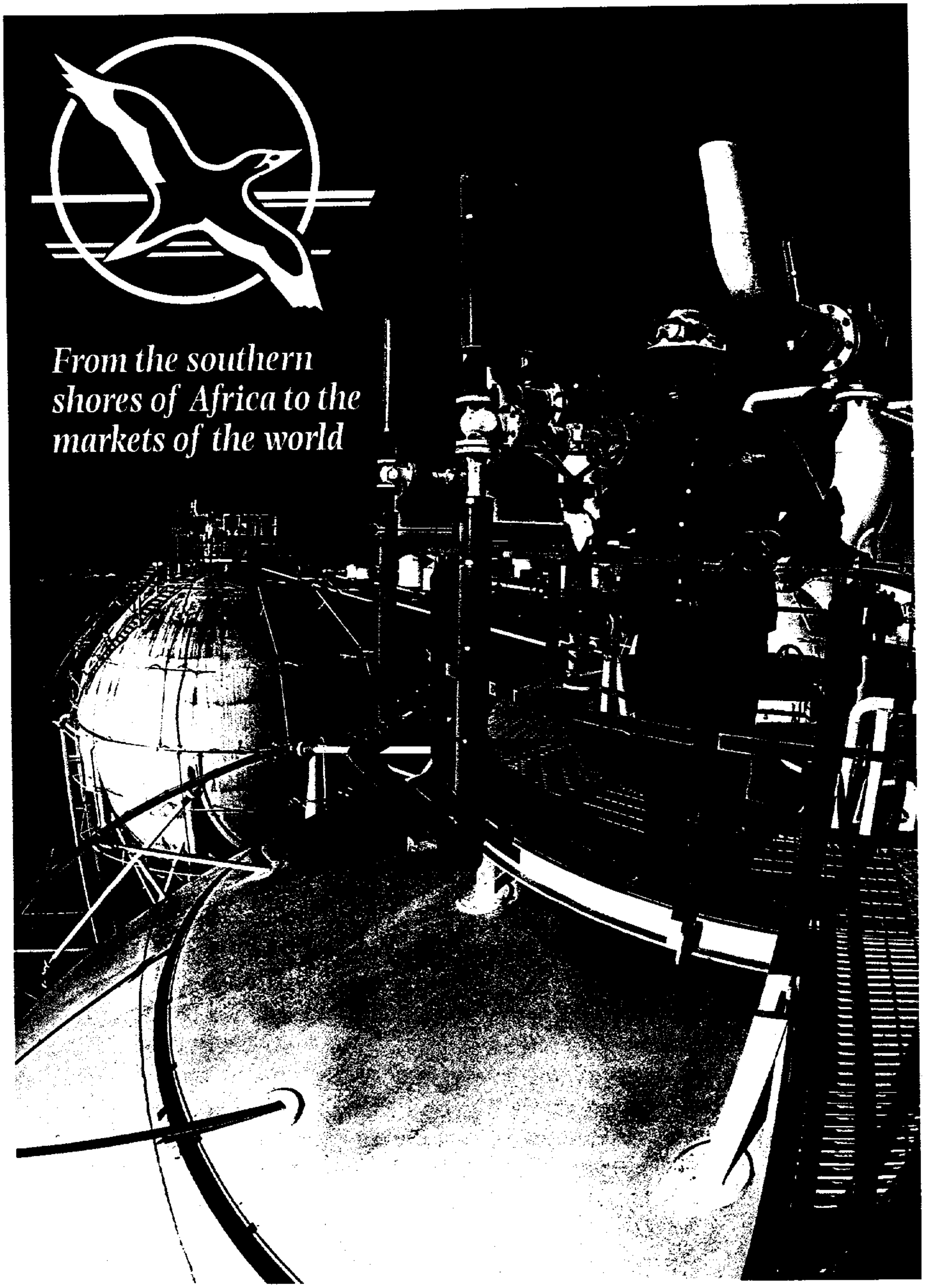
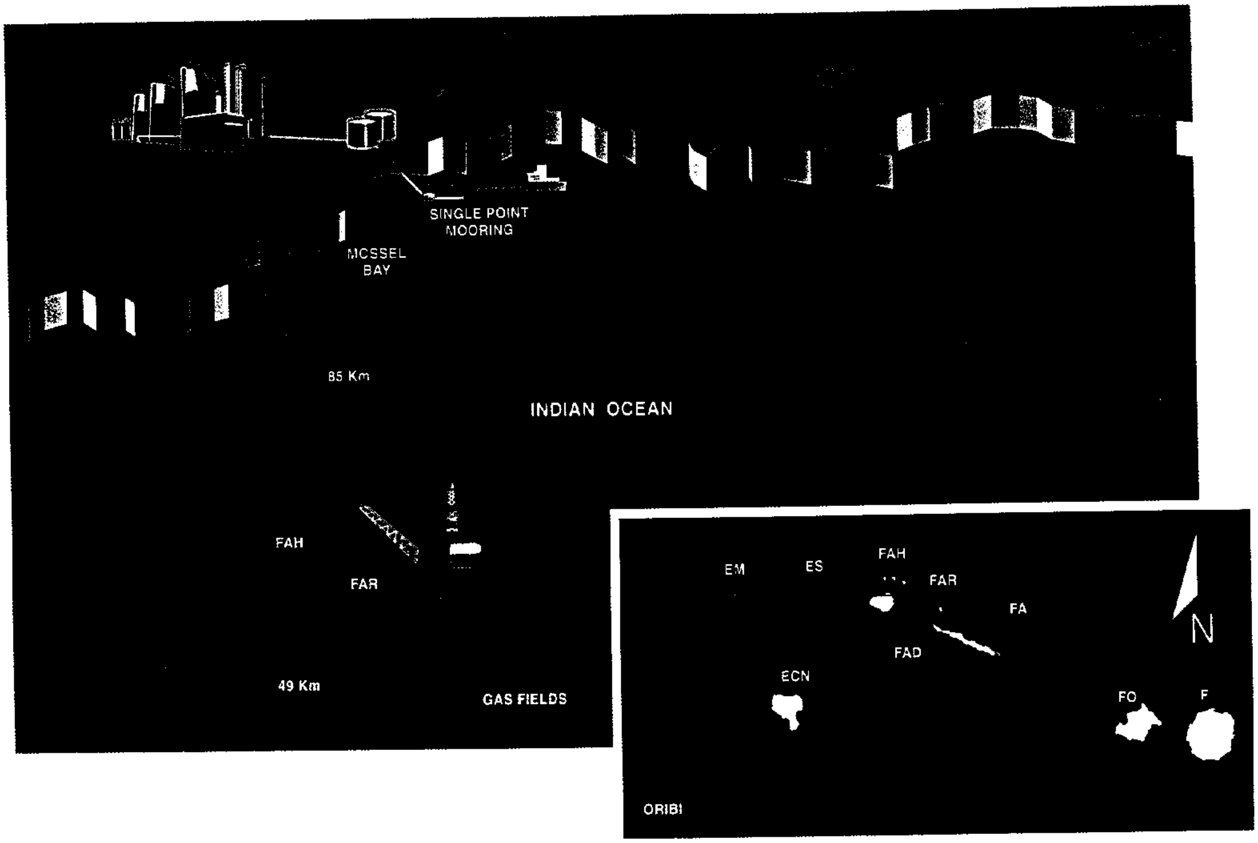
E-mail	**moscdk@mossnet.co.za**

Yours sincerely

Kobus Terblanche
Technical and Development Manager


From the southern shores of Africa to the markets of the world



SINGLE POINT MOORING
MOSSEL BAY
85 Km
INDIAN OCEAN
FAH
FAR
49 Km
GAS FIELDS
EM
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FA
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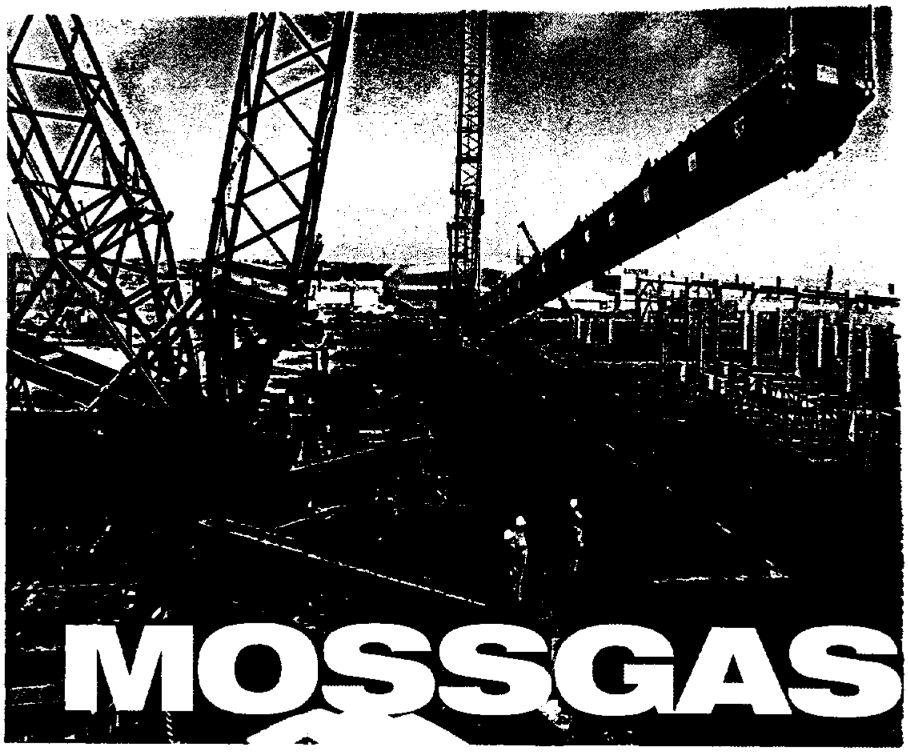


The search for crude oil in South Africa led to the first discovery of petroleum gas deposits in the continental shelf complex off the country's Southern Cape coast in 1969. This was followed by further discoveries that included the FA gas field in the Bredasdorp Basin in December 1980 and the EM field, 49 km west of FA, in January 1984.

The FA field, as well as some smaller satellite fields are situated 85 km south of Mossel Bay, a harbour town situated some 400 km east of Cape Town.

In February 1987 the South African Government announced the Mossgas project for the production of synthetic motor fuels from gas from these two fields to reduce the country's dependence on imported oil. This decision was reconfirmed in April 1988 and in May 1988 construction of the onshore plant began near Mossel Bay.

Local content targets

The fabrication of components for the onshore plant as well as the offshore production platform on the FA field started almost simultaneously at locations all over South Africa. Adherence to local content targets of 80% and 70% for the on- and offshore projects respectively resulted in only a limited amount of project fabrication work being done abroad.

The project phase involved more than 45 000 South Africans and a small number of foreign project management experts, engineers and artisans. This included about 16 500 people at the onshore plant during the construction peak period.

The offshore platform supplied the first gas to the onshore plant on 31 March 1992.

Construction of the onshore plant was completed in June 1992 and on 2 January 1993 the plant went into full production.

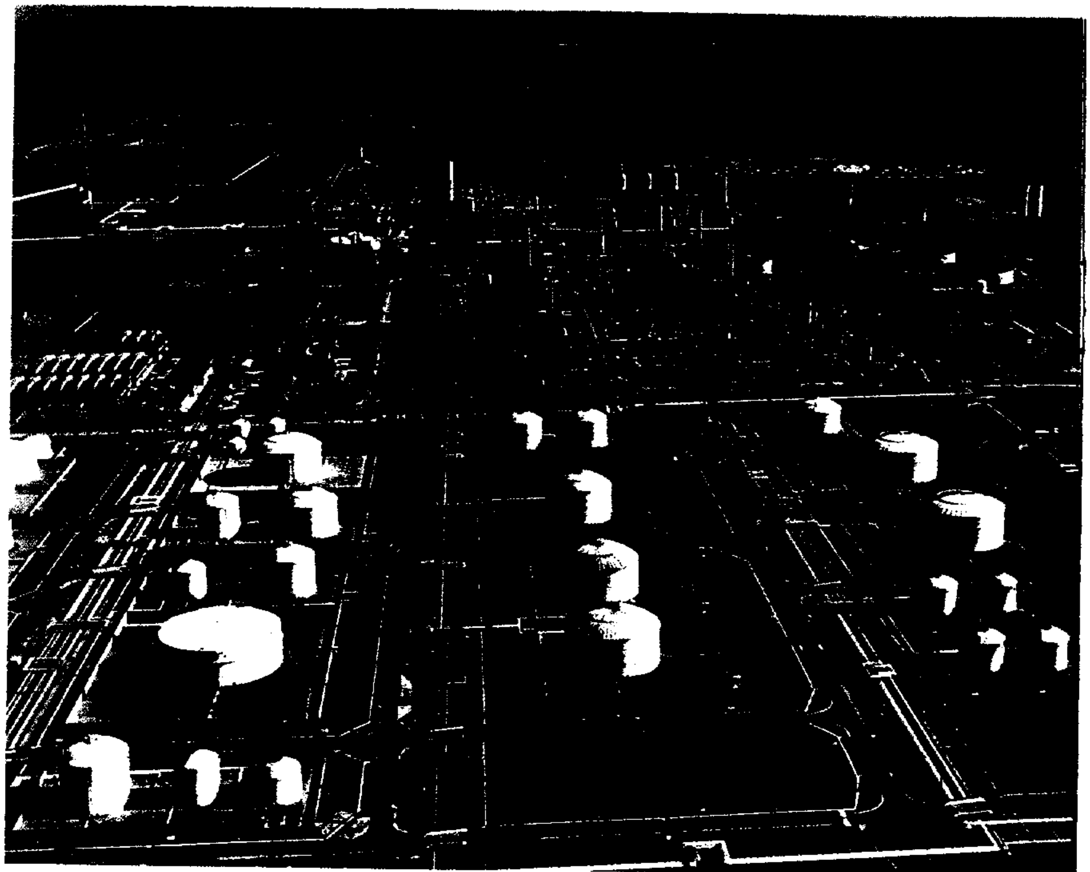
The original project plan included the commissioning of two nearby satellite fields, FAH and FAR, which are situated respectively 16 km and eight km north-west of the FA platform. It also made provision for the installation of a compression module on the platform to boost the flow of gas when the natural pressure in the production wells dropped to below the levels required for the optimal extraction of gas from the main field.

First satellite well

The South African Government approved the capital expenditure for these projects in mid-1996, and in May 1997 gas from the first satellite well, FAH4, reached the onshore plant.

The EM gas field, 49 km west of FA, is scheduled for commissioning in 2001 when the FA reserves run out. It will provide Mossgas with gas until the end of 2005.

Several other gas fields have also been identified during the search for oil in the Bredasdorp Basin. This gives reason for optimism that sufficient gas reserves are available off the Southern Cape coast to meet Mossgas' longer-term requirements.



The Mossgas onshore plant, west of Mossel Bay.

The company

Although the Mossgas project was launched in 1987, Mossgas (Pty) Limited in its present form was established in April 1989. It owns and operates the offshore production platform on the FA field as well as the onshore plant.

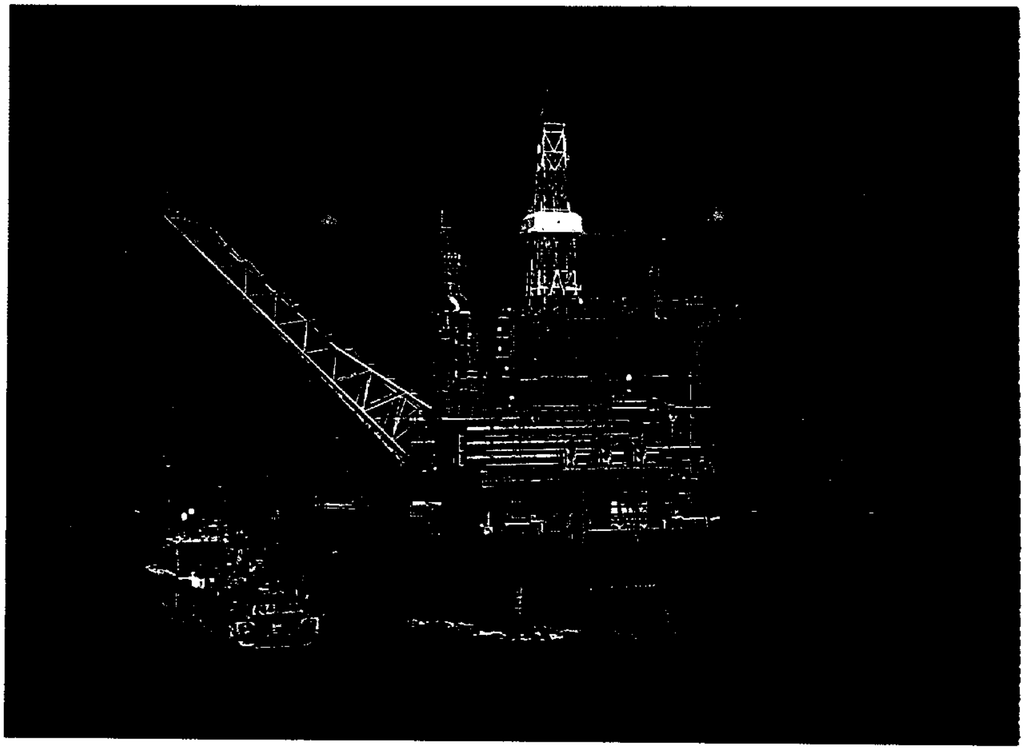
The company is part of the CEF group of companies through which the State's interest in the liquid fuel industry is owned, developed and managed commercially.

Each of these companies has its own Board which is appointed by the Minister of Minerals and Energy.

The business vision of Mossgas is to add value to the existing operation and to be restructured in due course in line with Government policy. Studies have shown that the company has substantial potential for the production of petrochemical derivatives such as ethylene, propylene and butylene.

Long-term programmes for Mossgas are dependent on the development of economically recoverable gas reserves in addition to those at present available to the company, or on supplementary feedstocks such as crude oil or petroleum condensate.

The production and marketing of high-value chemicals are however expected to justify further exploration for gas as well as the exploitation of identified reserves off the southern Cape coast.



The FA production platform in the Indian Ocean, 85 km southwest of Mossel Bay.

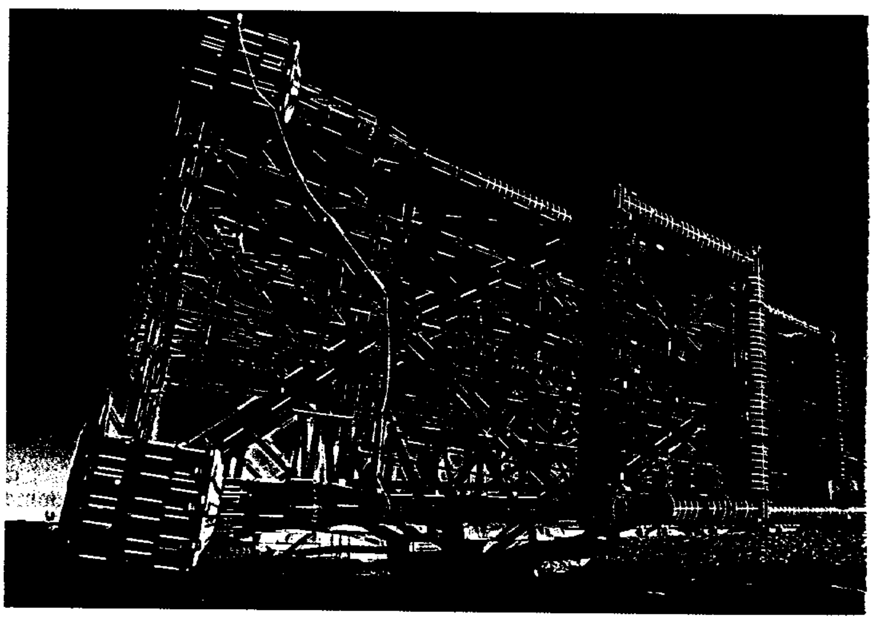
Offshore operation

Towering 114 metres above sea level and extending 105 metres below, the FA production platform is one of the largest single structures ever constructed in South Africa.

Supporting it all is a steel lattice structure or 'jacket', itself 124 metres high and weighing nearly 14 500 tons. The jacket is firmly fixed to the ocean floor by 24 piles, six on each leg and driven up to 122 metres into the seabed.

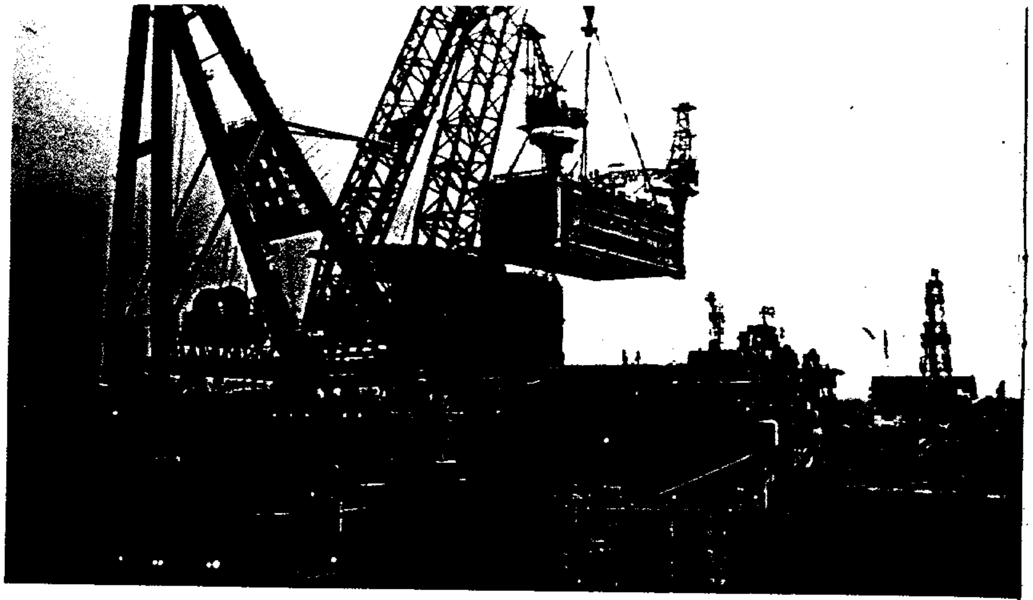
On top of the jacket is the module support frame that provides the base for eight dedicated modules. Each module, a fully equipped sub-assembly, is purpose-designed for its particular function.

They are the processing, well-head, utilities, power generation, drilling and drilling mud, compression (due for installation in 1998).



Jacket loaded onto a barge for the journey from Saldanha to the FA field.

Offshore personnel relaxing after shifts.



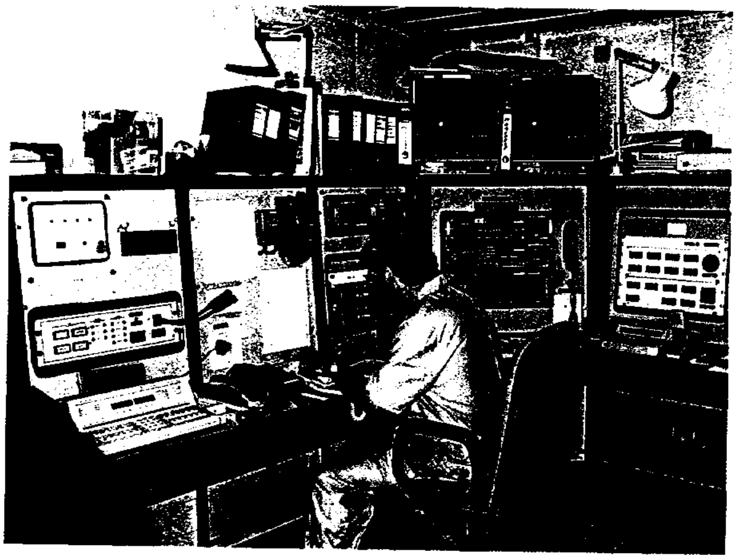
Drilling module being positioned on the FA platform.

and accommodation modules as well as a drilling derrick.

The gas and condensate are recovered from between 2 500 metres and 2 800 metres below the seabed. It is then piped ashore for processing into high quality liquid fuels as well as some alcohols.

Dedicated pipelines, one of 450 millimetres (18 inches) for gas, and one of 200 millimetres (8 inches) for condensate, link the platform to the onshore plant, 91 km away.

Nine production wells have been drilled from the platform. These include several which are inclined and tap gas and condensate more than four km away from the centreline of the platform. Four production wells on the FAR and FAH satellite gas fields are linked to the platform by sub-sea systems.



The radio room aboard the platform.

The platform sleeps 167 people in compact, yet comfortable cabins. Recreation facilities include a well-equipped gymnasium and a recreation room for pool and table games. There is also a lounge with TV and video facilities. Time on board varies, depending on specific duties, but is generally two weeks on, two weeks off.

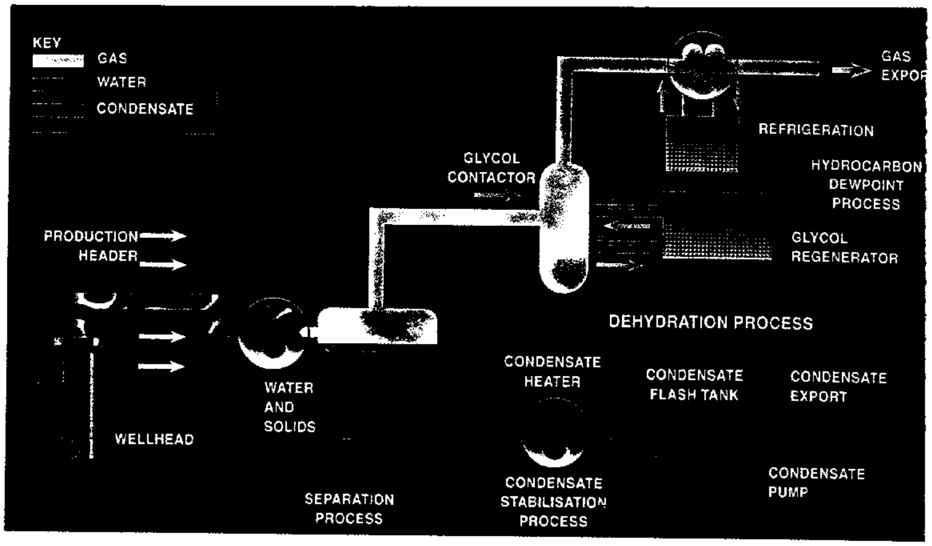
Safety is important in this type of environment. All crew members, as well as regular visitors, undergo emergency training. Safety and emergency drills are held regularly and medical assistance is available both on board and on call from the shore.

The accommodation module serves as a safe area since it is capable of withstanding temperatures of up to 1 000 °C for one hour.

A dedicated standby vessel, always in attendance, is fully equipped with fire fighting apparatus, sea rescue and medical facilities. Fast rescue boats as well as helicopters are available should the platform have to be evacuated.

Offshore process

Flow diagram for the offshore process.



The gas, condensate and water mixture flows under natural pressure from the production wells to the platform deck. This hot fluid is initially cooled to a temperature of 32 °C before entering a high-pressure separator where the gas, condensate and water are separated.

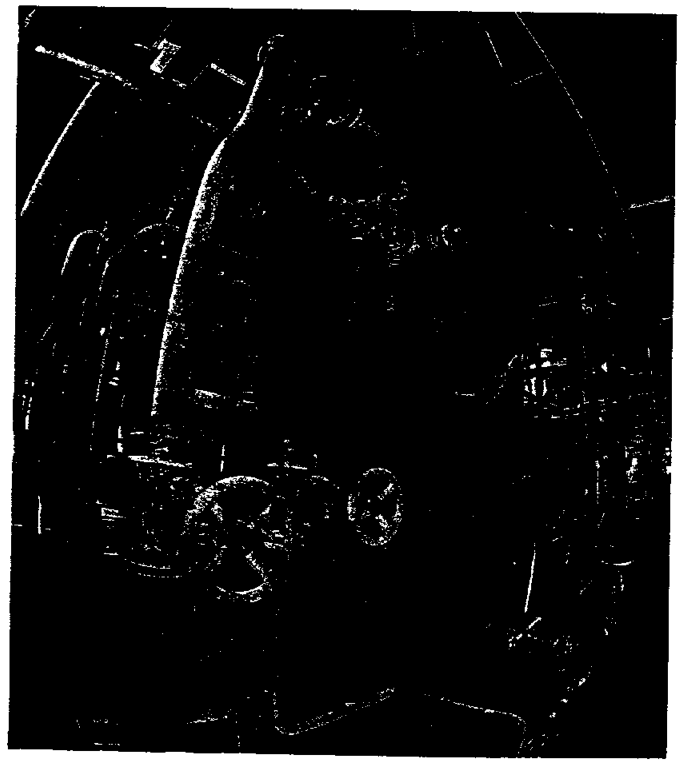
The water is first degassed, then treated to remove hydrocarbon traces, and finally discarded into the sea. Water vapour remaining in the gas is removed in a glycol contactor, while the remaining heavier fractions are condensed out by chilling the gas to −10 °C. The gas is then ready to be piped ashore under natural reservoir pressure.

The separated condensate is filtered and any remaining water removed in a coalescer. To drive off lighter components, the condensate is then heated and flashed in a raw condensate flashdrum. The gas that is removed by this process is routed back to the glycol contactor.

The remaining condensate, together with the condensate coming from the chilled gas, is again flashed to produce fuel gas for use on the platform and then pumped to the onshore plant.

A sample of the condensate which is recovered with the gas from below the seabed.

The glycol contactor on the FA platform.



The onshore plant.

Onshore operation

The onshore plant is situated 11 km west of Mossel Bay on a 410 hectare site on South Africa's scenic Garden Route. A modern solid waste disposal facility is situated next to the main plant on a property of 360 hectares.

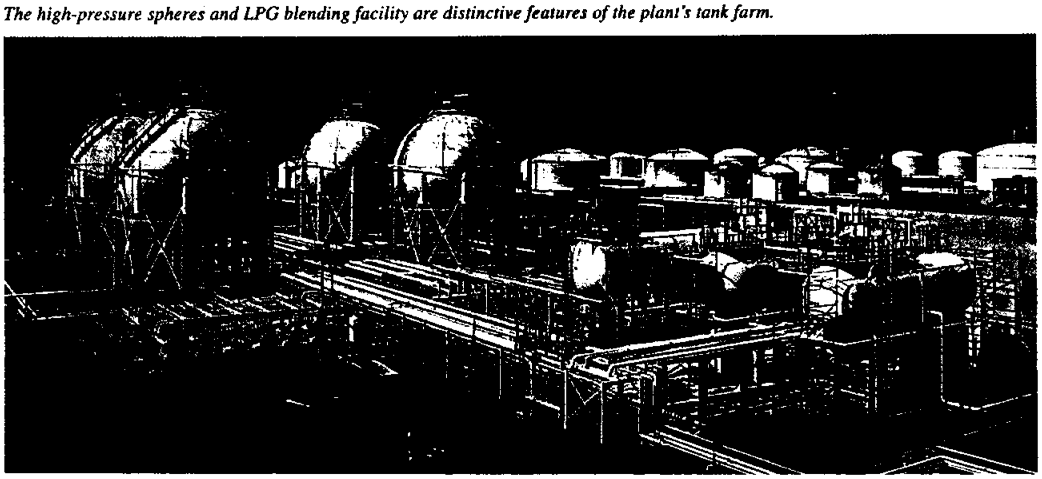
This high technology plant has a design production capacity of 30 200 barrels of refined products per day. This equates to 45 000 barrels of crude oil refined per day. The site is terraced which, together with the availability of ample space, has allowed for a safe and practical plant layout. Enough land is also available for future expansion.

The plant has 21 process units and 19 utility units. These include a facility to generate more than half of Mossgas' electricity requirements of 180 MW, gas liquefaction and storage facilities and reaction water, as well as raw water treatment facilities. It includes a tank farm and blending facilities. Rail and road loading facilities make provision for the dispatch of final product as well as the receipt on site of chemicals, catalysts, equipment and other materials.

Production activities are directed by a sophisticated computer system from a well-protected central control room. A modern laboratory also serves the plant.

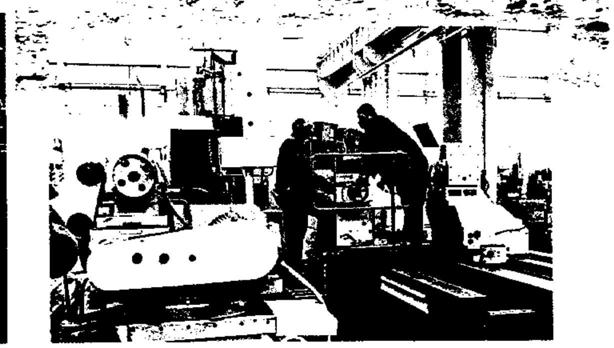
The majority of the finished products are piped overland to a second, smaller tank farm in the Voorbaai industrial area of Mossel Bay. Alcohols are transported in rail cars from the rail loading facility at the plant to special storage tanks at Voorbaai from where they are pumped into tankers via a conventional buoy mooring. Liquid petroleum gas (LPG) is also loaded into rail cars at the

The high-pressure spheres and LPG blending facility are distinctive features of the plant's tank farm.



A tanker loading alcohols for export at the conventional buoy mooring in Voorbaai.

The central control room and ...



... mechanical workshops at the onshore plant.

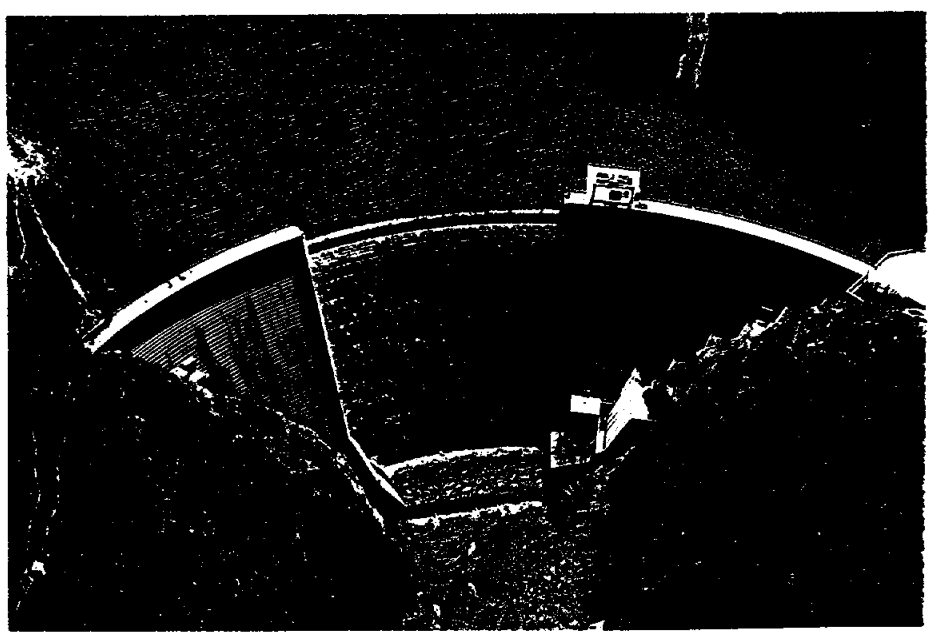
plant from where it is dispatched to distributors. A bundled pipeline connects the Voorbaai tankfarm to a single point mooring approximately three km offshore, and is used for loading liquid fuel tankers.

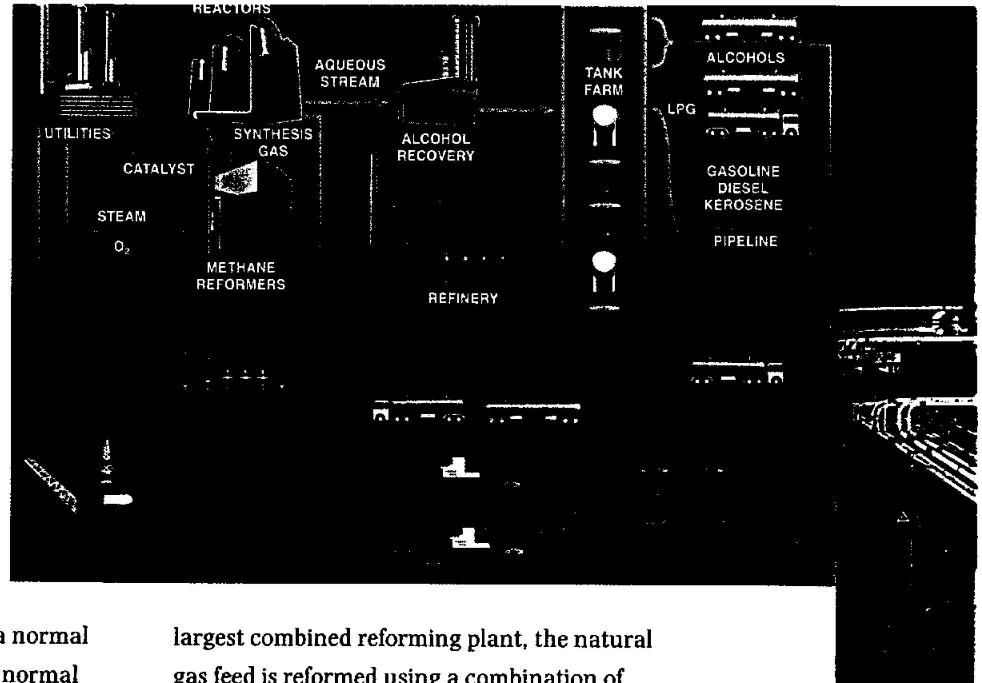
Mossgas' civil, electrical and mechanical workshops are equipped to handle even the most complicated maintenance requirements of this huge plant.

The company has its own fire station that is staffed to meet the special requirements of a large petrochemical facility. A medical station, manned by staff to deal with emergencies together with the day-to-day medical care of employees, is located on site.

The nearly six million cubic metres of water required annually for the onshore processes is supplied from the Wolwedans Dam, 30 km from the plant in the upper course of Great Brak River. The dam has a capacity of 24 million cubic metres.

The Wolwedans Dam provides the plant with approximately 6 million m^3 of water annually.





The Mossgas process.

Onshore process

The onshore plant receives gas at a normal operating rate of about 210 000 normal cubic metres per hour and the associated condensate at a rate of more than 9 000 barrels a day.

On arrival, the natural gas is first treated to recover the liquid petroleum gas range of materials, propane, butane and heavier. The gas is then routed to what is called the gas loop.

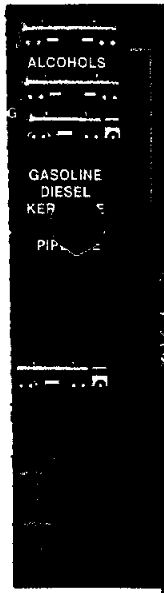
The gas loop essentially consists of two main sections, the methane reforming plant which is the largest of its kind in the world, and the Synthol plant which utilises the South African developed Synthol process. This is the heart of the plant and is where the natural gas is converted into synthetic oil.

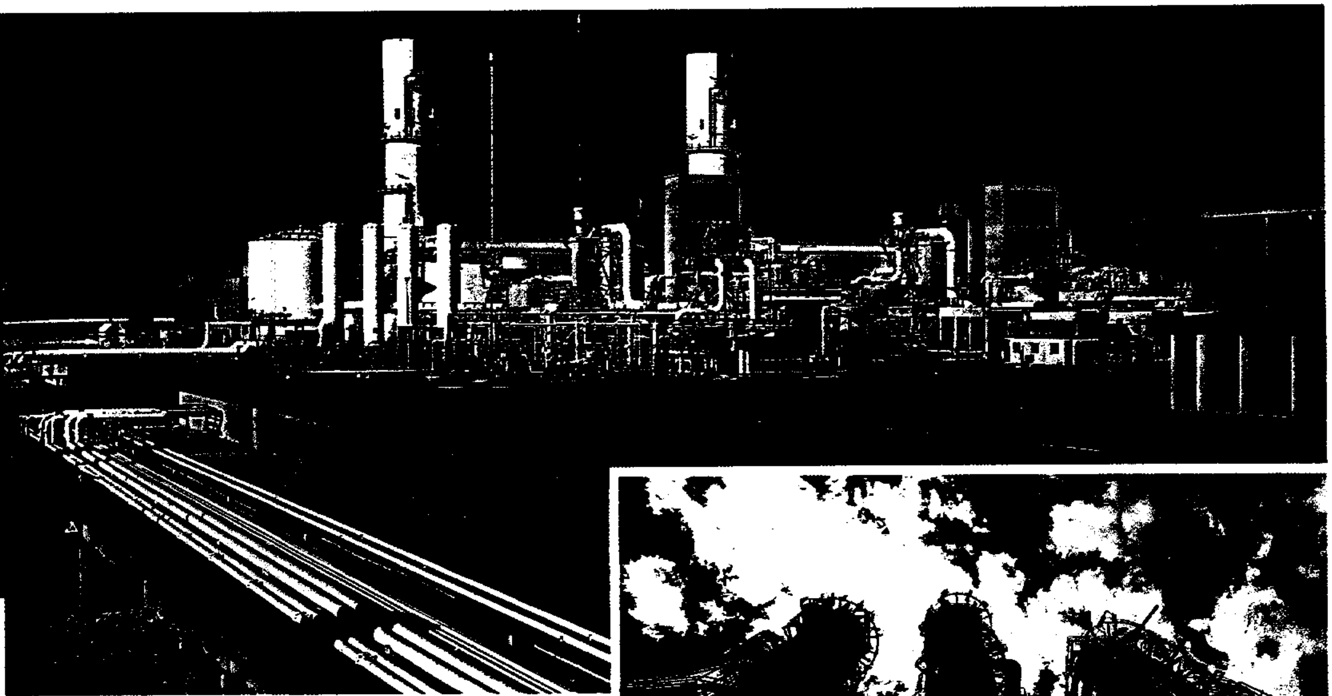
In the methane reforming plant, the world's largest combined reforming plant, the natural gas feed is reformed using a combination of primary steam reforming and oxygen blown autothermal secondary reforming. This plant consists of three identical trains, each having primary and secondary reforming capabilities.

An air separation unit produces the pure oxygen required for secondary reforming. It consists of two separate trains, each producing 63 000 normal cubic metres (90 000 kg) of pure oxygen per hour.

The product from the methane reforming plant is synthesis gas which consists mainly of hydrogen and carbon monoxide. This is fed into the Synthol plant, the second main section of the gas loop, for single step conversion into synthetic oil.

The methane reforming unit where the natural gas is transformed into a hydrogen-rich synthesis gas.





The air separation unit produces 180 t of oxygen per hour.

Distillation columns at the onshore plant.

The reactors in the Synthol plant are of the circulating fluidised bed type and the catalyst is manufactured on site. This plant also consists of three identical trains. Besides the synthetic oil, the plant produces a by-product stream of mixed alcohols.

Following the gas loop is a light oil refinery. The synthetic oil from the gas loop and the condensate are treated and upgraded to high quality motor fuel blend stocks. Conventional refining processes, hydrotreatment, catalytic reforming (platforming), isomerisation, catalytic polymerisation and alkylation are employed in the refinery.

The Synthol reactors where gas is transformed over a catalyst to yield synthetic oil.

Products and marketing

Mossgas produces a range of high quality, low sulphur and environmentally friendly fuels together with unique anhydrous blends of alcohols which conform to the exacting standards of the international markets.

Local distribution area.

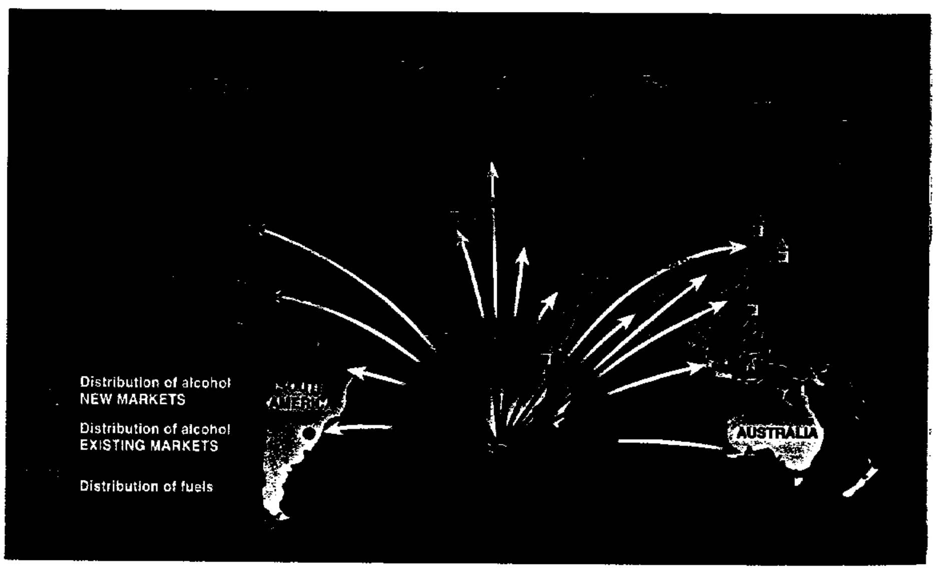
The primary product range consists of

- leaded 97 RON (road octane number)
- unleaded 95 RON gasoline
- diesel
- kerosene
- liquid petroleum gas (LPG)
- and fuel oil.

The bulk of Mossgas' production is supplied to the major South African oil companies which market it through retail networks under their own brand names in parts of the Western, Eastern and Northern Cape provinces of South Africa.

The gasoline, diesel and kerosene are shipped from a single point mooring at Mossel Bay to the coastal cities of East London and Port Elizabeth as well as to Europe, Africa and Asia. Mossgas also distributes products directly to the local market by road and rail from Mossel Bay.

In addition, Mossgas exports some diesel directly to Western Europe and to the Far East where it commands premium prices because of low sulphur and very low aromatic content, high cetane number and excellent cold flow properties.



More than 110 000 tons of light and heavy alcohols are produced annually which are exported to chemicals markets in Europe, Russia, South America, the Middle East, India and the Far East. The alcohols are used in chemical and industrial solvents, paint thinner components, de-icers and windscreen washes in sub-zero climates. They are marketed with a Kosher certificate.

Small quantities of carbon dioxide as well as liquid oxygen and liquid nitrogen are also produced and sold to local customers.

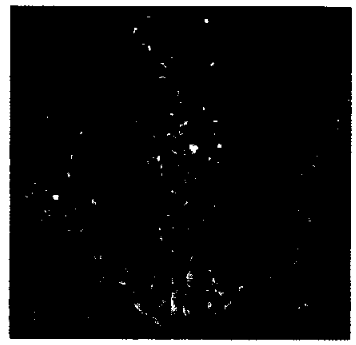
Human resources

Mossgas recognises that its employees are its most important asset and that its objectives can only be achieved through positive interaction with its employees. The Mossgas vision, mission and philosophy is evidence of the company's commitment to human dignity, people development and equity of opportunity.

It conducts an affirmative programme in terms of a policy which prescribes a total systems intervention and a positive initiative aimed at correcting the disadvantaged position of certain groups.

Owing to the relative shortage of suitably qualified people in the marketplace for this highly technological environment, Mossgas, through its own training activities, career pathing and succession planning, strives to identify and equip its employees for senior positions and specialist tasks. The company is committed to rewarding performance and commitment toward achieving company goals.

Safety, health, quality and the environment



Mossgas is committed to the safety and health of its employees, total quality of its products and processes, as well as the conservation and care of the environment in which it operates. As part of this commitment the company has adopted an integrated management system for safety, health, environmental management and quality control.

The onshore plant holds the National Occupational Safety Association of South Africa's (Nosa) top five-star grading. In May 1997 it won the 1996 National Safety Competition in the A-category for companies with more than a thousand employees. Mossgas has recorded one million man-hours without lost-time injuries on several occasions and has twice exceeded the two-million mark.

In November 1995 Mossgas received the SABS/ISO 9002 accreditation, making it one of a select group of South African companies adhering to the requirements for quality management of the South African Bureau of Standards and International Standards Organisation (ISO).

Mossgas is also a leader in the field of environmental care and extensive environmental impact studies preceded the construction and installation of its current facilities. Various measures to protect the environment such as smokeless flare stacks, high technology seals and water treatment facilities have been installed.

In November 1996 it became one of the first companies in South Africa to be certified in terms of the ISO 14001 standard for environmental management and control for the full extent of its operations.

A nature reserve adjacent to the refinery is an excellent example of a healthy co-existence between nature and a major industrial plant. It supports a teeming bird life as well as introduced animal species such as bontebok, springbok and zebra.

Of special interest to botanists is the more than 500 indigenous plant species which are protected in the reserve. This includes several rare or threatened species such as *Gladiolus Emiliae* which is found only in few pockets of undisturbed natural veld, such as the Mossgas Nature Reserve, between Swellendam and George.

Economics

Mossgas has a significant positive economic effect, particularly in the Southern Cape area.

Mossgas employs just over 1 000 people directly. The results of an official survey conducted in 1995 indicated that the company indirectly creates another approximately 7 000 job opportunities. Of these 3 000 are in the Southern Cape. Mossgas' purchases amount to approximately R1 billion per annum of which approximately 90% is spent in South Africa and R600 million is spent in the Western Cape.

The company produces approximately 8% of South Africa's total transportation fuel requirements at a rate of about 30 000 barrels of finished products per day. It contributes to foreign exchange savings of more than a billion rand per annum as a result of crude oil import replacements. In addition Mossgas earns in excess of R100 million per annum from alcohol exports.

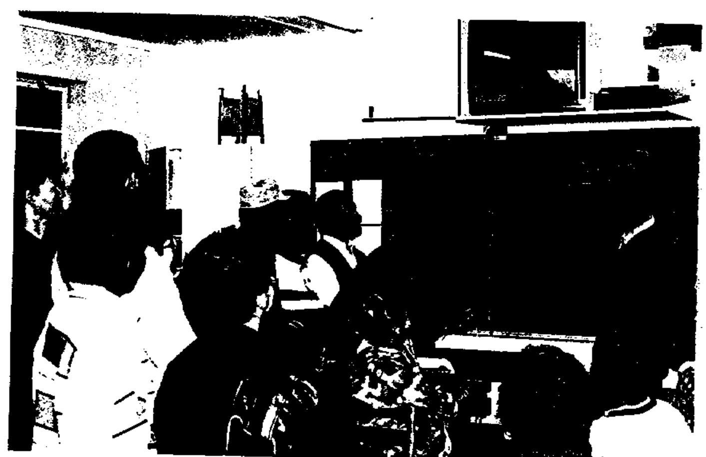
Mossgas has been achieving operating profits ever since its second full financial year, before taking into account certain State contributions for which it qualifies.

Social investment

The company acknowledges the importance of social investment, particularly in its home town of Mossel Bay. The main focus in this regard is on primary and secondary school education, adult education and economic empowerment of the previously disadvantaged communities.

Each of the more than 30 State or State-supported schools, including farm schools, in the Mossel Bay area receives an annual grant from the company, based on a sliding scale which takes school and community need level, as well as pupil numbers, into account.

A group of matriculants from schools in disadvantaged areas are admitted annually to the educational centre on company premises for special tuition in mathematics and physical science, as well as communicational English and life skills by teachers employed by the company for this purpose. The main objective of this year-long programme is to improve their matric results in mathematics and physical science to levels required for admittance to tertiary educational institutions. Bursaries for further studies are granted to top students.



The main focus of the company's social investment programme is on education.

Recent sponsorships included a refresher course in mathematics for more than 50 teachers from schools in disadvantaged areas.

Besides its internal affirmative action programmes, the company has launched an economic empowerment programme for previously disadvantaged people which focuses on direct business opportunities within the company as well as indirect opportunities through the utilisation of company facilities, utilities, products and waste materials to set up businesses.

These will be matched with existing or potential entrepreneurs who are, if necessary, assisted in acquiring appropriate business skills as well as formal qualifications which may be needed to meet the legal requirements required for a specific business or contract.

The Mossgas project alleviated the housing shortage in Mossel Bay by erecting 281 dwelling units for construction workers. These units were converted into conventional dwellings once construction was completed. Some were made available to employees but the majority was handed over to the local housing authority.

Apart from donations to welfare organisations, the company also sponsors local sports events.

As local recreational facilities were inadequate for the large number of construction workers, rugby and soccer fields as well as tennis courts were built in the KwaNonqaba and D'Almeida residential areas. These facilities, which are equipped with floodlights as well as ablution blocks, were donated to the respective communities on completion of the Mossgas construction phase.

The dining and recreation halls in four construction camps, two each in D'Almeida and KwaNonqaba were also transferred to these communities at the end of the construction activities.

The buildings are utilised for various purposes, ranging from medical clinics, welfare offices and a library to venues for indoor sports and public meetings.

A section of one of the dining and recreation halls built for construction workers is now utilised to house a group of street children.

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PETITION

FOR THE REGISTRATION

OF

MOSSGAS “GAS-TO-LIQUID” FUELS

AS

“ALTERNATIVE FUELS”

UNDER EPACT

Author: C Knottenbelt

1999-09-09

MOSSGAS

MOSSGAS REFORMULATED DIESEL FUELS FOR EPACT APPROVAL

SUMMARY

Mossgas (Pty) Limited, located in Mossel Bay, South Africa, requests that the US Department of Energy (DOE) approve its "gas to liquid" reformulated diesel (RFD) fuels as "alternative fuels" under the regulatory authority of the Energy Policy Act of 1992 (**EPACT**).

Mossgas is a South African Government owned company, which is managed according to sound commercial practices. Mossgas converts natural gas to synthetic fuels.

The Mossgas low sulfur gas to liquid synthetic diesel fuels are substantially non-petroleum and provide substantial energy security benefits by means of energy diversification.

The RFD diesel fuels are totally transparent to the end user in that they can be used in any comparable conventionally fueled diesel vehicle with no engine modifications.

Emission testing performed by West Virginia University, the National Renewable Energy Laboratory and the U.S. Department of Energy proved that the use of Mossgas RFD fuels in heavy vehicles resulted in reduced emissions when compared to conventional fuels and thus yielded substantial environmental benefits.

INTRODUCTION

The Energy Policy Act of 1992 was enacted to stimulate research, development, and accelerate the introduction of alternative fuels and technologies into the United States.

EPACT objectives:

- To identify "alternative fuels" that are substantially not petroleum (crude) based,
- To promote energy diversity and the displacement of crude-oil based motor fuels and
- To identify low emission fuels that are produced responsibly and that will substantially benefit the environment.

The primary feedstock for the Mossgas gas to liquid (GTL) process is natural gas, which is considered not petroleum based for the purposes of EPACT.

The first step of the GTL process entails the production of synthesis gas whereby carbon monoxide and hydrogen are produced by steam reforming natural gas. The second step involves the high-temperature Fischer-Tropsch Technology whereby the synthesis gas is converted to liquid hydrocarbons and olefinic gases.

The olefinic gases are then fed to the Mossgas Conversion of Olefins to Distillate (COD) unit that oligomerises olefins to form quality distillates and gasoline components. The COD distillate once hydrotreated is the majority component of the RFD Mossgas Diesel.

The Mossgas Reformulated Diesels (RFD) exhibits excellent properties for use in compression ignition engines including:

- Excellent cold flow properties
- Low sulfur (typically less than 10 ppm)
- Energy content similar to US Pump Diesel
- Cetane number of greater than 48
- Suitable for use in unmodified light and heavy duty diesel engines
- Transportable within the existing US diesel fuel infrastructure
- Excellent emission benefits, including heavy duty diesel engines
- Excellent compatibility with exhaust gas reticulation (EGR) systems and aftertreatment technologies such as particulate traps and filters, oxidation catalysts, lean nitrous oxide catalysts and selective catalytic reduction devices.

MOSSGAS

Mossgas (Pty) Limited is a South African Government owned company and commercially managed. Mossgas converts off-shore natural gas to synthetic liquid fuels.

Mossgas was established in 1989 as part of the South African Government Company, Central Energy Fund (Pty) Limited (CEF). The natural gas rig is situated 80 km off-shore from Mossel Bay and the onshore plant is situated 11 km west of Mossel Bay on South Africa's south-eastern coast. This plant produces 30 200 barrels of refined products per day. A total of 1008 tons of diesel is produced per day.

The onshore plant holds the National Occupational Safety Association of South Africa's (NOSA) top five-star grading. In November 1995 Mossgas received the SABS/ISO 9001 accreditation, making it one of a select group of companies adhering to the requirements for quality management of the International Standards Organization (ISO).

Mossgas is a leader in the field of environmental care and extensive environmental impact studies preceded the construction of the plant. In November 1996 Mossgas was certified in terms of the ISO 14001 standard for environmental management and control for the full extent of the onshore and offshore operations.

Based on the excellent reformulated diesel (RFD) fuel characteristics, the responsible production thereof by Mossgas and with due emphasis on environmental protection, Mossgas believes that there are sufficient grounds to consider EPACT registration.

Mossgas hereby petitions the United States Department of Energy to approve the Mossgas synthetically derived "gas to liquid" diesel fuels as "Alternative Fuels" under the regulatory authority of the Energy Policy Act of 1992.

The proposed fuels are:

- Mossgas Reformulated Diesel 1 (RFD 1)
- Mossgas Reformulated Diesel 2 (RFD 2)
- Mossgas Reformulated Diesel 3 (RFD 3)

FUEL CHARACTERISTICS

Mossgas has selected three RFD formulations to be considered for EPACT registration. COD syndiesel forms the majority component (greater than 60%) in the 3 proposed formulations, while Synthetic Light Oil (SLO) syndiesel component from the Fischer-Tropsch process forms the second largest component. A portion of mixed heavy alcohols is used in the blend RFD 3. These anhydrous alcohols are also synthetically derived products from the Mossgas GTL process. The blends RFD 1 and RFD 3 contains 7 percent diesel component derived from the light condensate which does not form part of the GTL synthetic diesel portion.

Table 1: Composition, by percentage volume, of the Mossgas RFD formulations.

COMPOSITION	RFD 1	RFD 2	RFD 3
COD Syndiesel	63	68	60
SLO Syndiesel (Fischer-Tropsch)	30	32	28
Condensate Diesel	7	0	7
Mosstanol 120 – Heavy alcohol	0	0	5
Non-Petroleum Portion (Gas to Liquid Fuels)	93	100	93

The RFD fuels are 93 to 100 percent non-petroleum. The non-petroleum portion being derived solely from "gas to liquid" fuels technology and are thus by definition, not petroleum-based.

In chemical and physical composition the Mossgas RFD fuels are completely transparent with conventional fuels and as such they have been used commercially in South Africa in all the commercially available vehicles powered by an unmodified internal combustion engine that utilize diesel as it's fuel source.

The following paragraphs detail the diesel's compositions. Tables 2 and 3 indicate the diesel fuels full technical specifications and typical values respectively.

The calorific value of the fuels as tested by IP 12 for the 3 RFD fuels are 135540, 137594, and 133526 Btu/gallon (gross) for RFD 1, RFD 2 and RFD 3 respectively. Expressed as US gallon equivalents the amount of RFD fuel containing the same energy content (138700 Btu) per gallon of fuel, is 1.023, 1.008 and 1.038 US gallons for the respective fuels.

The fuels boil in the typical diesel distillation range from approximately 220°C (392°F) to 365°C (689°F) as tested by ASTM D86. Due to the presence of heavy alcohols in the RFD 3 blend the initial boiling point is lowered to 81,3°C (176°F). The alcohols were added specifically for applications where ultra low particulate matter (PM) emissions are of importance, and their excellent compatibility with aftertreatment devices.

The ultra-low sulfur content of less than 10 parts per million (ppm) mass is seen as one of the Mossgas RFD diesel fuel's greatest attributes. This meets all advanced diesel specifications and is ideally suited for advanced compression ignition engine technologies, fuel cell fuels and hybrid electric vehicles. Workshop participants at the January 21, 1999 DOE Workshop for "Emission Control Strategies for Internal Combustion Engines" held at Tucson, Arizona concluded that ultra low sulfur diesel (<30 ppm) was a definite low emission fuel requirement and would enable the use of several catalytic exhaust aftertreatment options [1]. Exhaust aftertreatment devices will probably be required to meet emission challenges beyond the heavy duty compression ignition standards promulgated for the year 2004, however they will require very low sulfur levels of less than 30 mg/kg. The Mossgas diesel RFD range already meets this challenge.

The Mossgas production process does not require the use of any sulfur removal technologies, but instead relies on the zero sulfur nature of the feedstock natural gas used. However similar commercial processes using a higher sulfur gas content would use conventional sulfur removal technology, as the nature of the Fischer-Tropsch process requires low sulfur feed material.

The fuel has good ignition performance characteristics, with a minimum cetane number of 48 as tested by ASTM D613.

Due to the large portion of iso-paraffins present in the RFD fuels the low temperature operability is exceptional and provides fuel flow even at sub-zero temperatures such as those experienced in cooler geographical regions of the USA. Cold Filter Plugging Point (CFPP) (IP 309) is used to characterize low temperature operability of diesel, the Mossgas RFD fuels CFPP values are typically in the range of minus 20°C (-4°F) and lower.

The relatively low aromatic (IP 391) content specification of each fuel is less than 18% by volume. The bulk of the aromatics are single ring mono-aromatics, with no detectable hazardous poly-aromatic species.

The level of mono-aromatics is approximately half that of conventional crude `derived diesel fuel and has been selected to ensure a balance between low emissions and vehicle operability. In the case where diesels containing less than 5% volume aromatics have been used to substitute crude derived diesel markets, diesel fuel pump seal failures were experienced as in the case when CARB diesel was initially introduced in California in 1993.

Table 2: Technical Specifications for the Fuels.

ANALYSES	UNITS	METHOD	RFD 1	RFD 2	RFD 3
Color	ASTM	ASTM D1500	1.5 max	1.5 max	1.5 max
Appearance		Visual	Clear & bright	Clear & bright	Clear & bright
Density @ 20°C	kg/l	ASTM D4052	0.800 min	0.800 min	0.800 min
Density @ 15°C	kg/l	ASTM D4052	0.804 min	0.804 min	0.804 min
Distillation		ASTM D86			
I.B.P.	°C (°F)		200 (392) min	200 (392) min	80 (176) min
10% (v/v) recovery	°C (°F)		240 (464) max	240 (464) max	240 (464) max
50% (v/v) recovery	°C (°F)		260 (500) max	260 (500) max	260 (500) max
90% (v/v) recovery	°C (°F)		340 (644) max	340 (644) max	340 (644) max
F.B.P.	°C (°F)		365 (689) max	365 (689) max	365 (689) max
Flash Point	°C (°F)	ASTM D93	62 (144) min	62 (144) min	20 (68) min
Kin. Viscosity @ 40°C	CSt	ASTM D445	2.2 – 4.0	2.2 – 4.0	2.1 - 4.0
C.F.P.P.	°C (°F)	IP 309	Max –20 (-4)	Max –20 (-4)	Max –20 (-4)
Ash	% m/m	ASTM D482	0.01 max	0.01 max	0.01 max
Sediment by Extraction	% m/m	ASTM D473	0.01 max	0.01 max	0.01 max
Water content	% v/v	ASTM D1744	0.015 max	0.015 max	0.020 max
Carbon residue, Rams	% m/m	ASTM D4530	0.2 max	0.2 max	0.2 max
Total Sulphur	% m/m	ASTM D2622	0.001 max	0.001 max	0.001 max
Copper Corrosion					
(3h @ 100°C)	Rating	ASTM D130	No. 1 max	No. 1 max	No. 1 max
Strong Acid Number	mg KOH/g	ASTM D974	Nil	Nil	Nil
Acid Number	mg KOH/g	ASTM D974	0.25 max	0.25 max	0.25 max
Cetane Number		ASTM D 613	48 min	48 min	48 min
Aromatic Content	% v/v	IP 391	18 max	18 max	18 max
Poly-Aromatic Content	% v/v	IP 391	0.2 max	0.2 max	0.2 max
Lubricity at 60°C	Microns	H.F.R.R.	450 max	450 max	450 max
Oxidation Stability	mg/100 ml	ASTM D2274	2 max	2 max	2 max

Table 3 - Mossgas RFD Typical Values

ANALYSES	UNITS	METHOD	RFD 1	RFD 2	RFD 3
Color	ASTM	ASTM D1500	L1.5	L1.5	L1.5
Appearance		Visual	Clear & bright	Clear & bright	Clear & bright
Density @ 20°C	kg/l	ASTM D4052	0.8088	0.8066	0.8065
Density @ 15°C	kg/l	ASTM D4052	0.8125	0.8103	0.8102
Distillation		ASTM D86			
I.B.P.	°C (°F)		221.7 (431.1)	225.8 (438.4)	81.3 (178.3)
10% (v/v) recovery	°C (°F)		236.6 (457.9)	235.8 (456.4)	238.5 (461.3)
50% (v/v) recovery	°C (°F)		254.9 (490.8)	255.3 (491.5)	250.8 (483.4)
90% (v/v) recovery	°C (°F)		322.5 (612.5)	324.0 (615.2)	317.5 (603.5)
F.B.P.	°C (°F)		360.4 (680.7)	362.6 (684.7)	363.3 (685.9)
Flash Point	°C (°F)	ASTM D93	100.5 (212.9)	102.5 (216.5)	20.0 (68.0)
Kin. Viscosity @ 40°C	CSt	ASTM D445	2.784	2.781	2.175
C.F.P.P.	°C (°F)	IP 309	-25 (-13)	-23 (-9.4)	-24 (-11.2)
Ash	% m/m	ASTM D482	<0.01	<0.01	<0.01
Sediment by Extraction	% m/m	ASTM D473	<0.01	<0.01	<0.01
Water content	% v/v	ASTM D1744	0.006	0.006	0.016
Carbon residue, Rams	% m/m	ASTM D4530	0.01	0.01	0.01
Total Sulphur	% m/m	ASTM D2622	<0.001	<0.001	<0.001
Copper Corrosion					
(3h @ 100°C)	Rating	ASTM D130	1A	1 A	1 A
Strong Acid Number	mg KOH/g	ASTM D974	Nil	Nil	Nil
Acid Number	mg KOH/g	ASTM D974	0.001	0.001	0.001
Cetane Number		ASTM D 613	53.0	49.4	49.3
Aromatic Content	% v/v	IP 391	16.4	15.6	15.9
Poly-Aromatic Content	% v/v	IP 391	<0.1	<0.1	<0.1
Calorific Value	Btu/gallon	IP 12	135 540	137 594	133 526
Lubricity at 60°C	Microns	H.F.R.R.	<400	<400	<400
Oxidation Stability	mg/100 ml	ASTM D2274	0.1	0.1	0.1

The addition of a commercial lubricity additive such as Paradyne 655 or Addibis ADX 4101 B at 200 parts per million (mass) treatment rates are recommended to meet acceptable lubricity levels for the Mossgas RFD fuels.

A study performed by the Centre for Automotive Engineering of the University of Stellenbosch in South Africa (CAE) found that longer oil drain intervals could be achieved in diesel-fueled light commercial vehicles using the low sulphur Mossgas RFD fuels as opposed to higher sulphur crude-derived pump diesel [2].

SUBSTANTIAL ENERGY SECURITY BENEFITS

The Mossgas gas to liquid fuels process offers substantial energy security benefits by means of energy diversification utilizing natural gas as a source of transport fuels and thereby reducing the dependency on crude derived petroleum based diesel fuels. Commercial plants operating today on the natural gas to liquid fuels principle and applying the Fischer-Tropsch technologies are:

- Mossgas Mossel Bay, South Africa
- Shell Bintulu, Malaysia

SASOL in South Africa use coal as a source of carbon.

The Mossgas process, utilizing natural gas as a primary process feedstock proves that natural gas reserves can be commercially processed and the products be converted into high quality liquid fuels. These fuels can be used in the existing fueling infrastructure, in either unmodified diesel fueled vehicles or in the next generation EGR and aftertreatment device-equipped engines and vehicles.

MOSSGAS REFORMULATED DIESEL FUEL PRODUCTION PROCESS.

The relevant core technologies used at Mossgas for synthesizing the RFD are:

- Natural gas reforming to produce synthesis gas
- Fischer-Tropsch technology to synthesize gaseous products and liquid fuels
- Oligomerisation to convert the gaseous product to liquid fuels
- Conventional refining technologies to further refine these products to the marketed transport fuels

The process can be followed in the attached schematic diagram, Figure 1. See page 29.

Gas receiving and processing

The plant receives gas at a normal operating rate of 200 000 Nm^3/h plus condensate at 65 Nm^3/h in separate pipelines. In the natural gas liquid recovery plant (NGL-REC) any hydrocarbons heavier than ethane are removed from the gas stream. This dry gas is termed lean natural gas. The condensate arriving from offshore is stabilized (in the NGL-REC) by the removal of light hydrocarbons.

Reforming

The lean natural gas (largely methane and ethane), together with excess propane from NGL-REC, is reformed using a combination of steam (primary) reforming and oxygen fired (secondary) reforming. Synthesis gas produced by methane reforming consists of carbon monoxide, carbon dioxide and hydrogen. The oxygen for the secondary reforming is produced in the air separation unit.

It should be noted that the synthesis gas feedstock could also be produced from coal gasification as used in the traditional "coal to liquid" fuels production processes.

The carbon dioxide content of the synthesis gas is adjusted to suit the Fischer-Tropsch synthesis process. Carbon dioxide removal is by absorption with mono-ethanol-amine.

The reforming reactions are as follows:

Nickel catalyst

Primary reforming $CH_4 + H_2O \rightarrow CO + 3H_2$

$CO + H_2O \rightarrow CO_2 + H_2$

Secondary reforming $CH_4 + H_2O \rightarrow CO + 3H_2$

$CO + H_2O \rightarrow CO_2 + H_2$

Hydrogen for use in other plant areas such as distillate hydrogenating is extracted from the CO_2 free gas in a pressure swing absorption unit (Hydrogen Purification).

Synthol Synthesis

The synthesis gas is catalytically reacted in the presence of a circulating fluidised bed of iron catalyst (the Synthol unit). The resulting Fischer-Tropsch (F-T) reactions yields a stream of synthetic light oil (SLO) and other products, namely an aqueous reaction water stream containing oxygenated (acid and non-acid) chemicals as well as tail gas consisting of methane and unreacted gas.

Synthol Reactions:

Iron catalyst

$$nCO + 2nH_2 \rightarrow (-CH_2)n + nH_2O$$

$$CO + H_2O \rightarrow CO_2 + H_2$$

$$nCO + 2nH_2 \rightarrow H(-CH_2)nOH + (n-1)H_2O$$

The Fischer-Tropsch reactor effluent is quenched to recover a heavy hydrocarbon stream (Decant Oil). The quenched reactor effluent is further cooled to recover a light synthetic oil stream and an aqueous stream containing alcohols. This is processed in the alcohol recovery unit.

Tail gas from the Synthol unit is sent to the tailgas treatment plant where products (propylene, butylene and C5/C6 condensate) are cryogenically removed before the gas is recycled to the gas reforming stage. These light olefinic products are used as the feed to the Mossgas Conversion of Olefins to Distillate (COD) plant.

Alcohol Recovery

The non-acid chemicals stream from the alcohol recovery unit distillation process is hydrogenated over a nickel-based catalyst to convert aldehydes, ketones and esters to their corresponding alcohol's.

Water Treatment

The reaction water containing organic acids is neutralized with calcium hydroxide and are then treated anaerobically and aerobically to reduce the chemical oxygen demand to meet cooling water standards. The treated reaction water is then recycled as process cooling water.

Methane produced by the anaerobic process (currently being flared) is planned to co-feed a 20 Mega Watt electricity turbine power generator.

Synthol Oil Fractionation

The Oil Fractionation unit is used to process the SLO and Decant Oil from the Synthesis unit for upgrading to transportation fuels in conventional refinery units. The product streams are:

- C5/C6, C5 -120°C olefins to be processed in COD unit.
- Naphtha for treating in a Hydrotreater

- SLO Distillate for treating in the Distillate Hydrotreater
- Heavy residue for Fuel Oil.

Conversion of Olefins to Distillate (COD)

The function of this unit is to oligomerise olefinic compounds over a shape selective zeolite catalyst to form longer chain molecules. This unit is selective towards the production of liquid transportation fuels and can be run either in a gasoline mode or a distillate mode of operation [3]. The major portion of the proposed Mossgas RFD fuels is produced in this unique unit.

Feeds to the unit could vary from olefins such as propylene, butylene, C5/C6 and C5 -120°C olefins.

COD Reactions:

Zeolite catalyst

$2C_3H_6 \rightarrow C_6H_{12}$ dimerisation

$2C_4H_8 \rightarrow C_8H_{10}$ dimerisation

$C_3H_6 + C_4H_8 \rightarrow C_7H_{14}$ dimerisation

Distillate Hydrotreating

In the distillate hydrotreating unit the olefinic intermediate products are hydrogenated over a nickel-molybdenum catalyst.

COD and SLO distillates are hydrogenated over a conventional nickel-molybdenum catalyst. Once hydrotreated, naphtha, kerosene and diesel products are fractionated from the distillate.

It should be noted that the Mossgas production process does not require the use of any sulfur removal technologies.

DISTRIBUTION OF FUELS

Unlike most other "alternative fuels" the Mossgas RFD diesels are in the liquid phase at ambient and sub zero conditions and can be transported and distributed in the existing petroleum refueling infrastructure without any modifications.

The fuel tank flammability is similar to that of conventional diesel. Two of the fuels have a flash point (ASTM D93) minimum specification of greater than 62°C (144°F), RFD 3 is the exception due to the presence of low flash point mixed heavy alcohols and flashes at 20°C (68°F).

PRODUCTION ENERGY BALANCE

An overall production energy balance on a total product per total hydrocarbon feed of 65 percent mass is achieved. This equates to 1.18 kg of hydrocarbons required to produce one liter of product.

By products produced by the process are water, fuel gas and carbon dioxide. Water produced in the process described above is recycled and used as cooling water feed for the cooling towers. Fuel gas produced in the process is used as heating gas.

Mossgas produces 0.45 Nm^3 of carbon dioxide per kilogram of product produced. This figure includes all sources over the entire process including activities such as water treatment, imported electricity emissions and all refining operations. The bulk of this carbon dioxide is produced in the reforming process, as is common to all commercial natural gas to liquid fuel, Fischer-Tropsch based processes. Part of the carbon dioxide produced is sold to downstream processors such as the specialty gas manufacturers and carbonated soft drink industries. Currently new markets for carbon dioxide are being exploited.

The final commercial products include leaded (97 RON) and unleaded (95 RON) petrol, diesel, kerosene, low sulfur fuel oil, liquid petroleum gas, alcohols and propane. All the products have been sold in the South African market since the commissioning of the plant in 1990.

FUEL CONSUMPTION IN HEAVY DUTY VEHICLES

The Mossgas COD syndiesel, the major component (60% plus) of the Mossgas RFD diesel range was tested independently by West Virginia

University, National Renewable Energy Laboratory and Department of Energy as an "alternative fuel" for use in heavy duty vehicles.

The fuels were evaluated in a 1999-model year 40-foot transit bus (made by TMC), using a four-stroke Detroit Diesel Corporation Series 50 direct injection engine, certified to 1998 transit bus emissions standards (8.5 liter, 275 hp). This New York Transit Authority (NYCTA) bus was tested over the CBD cycle, the New York City Bus Cycle and a newly developed cycle termed Route 22.

The Mossgas diesel was compared to a Regular Federal 49-state number 2-diesel fuel (D2) on the WVU chassis dynamometer.

Fuel consumption results highlighted that the Mossgas COD diesel fuel has a similar consumption to that of the Regular Federal 49-state no. 2 diesel, while substantial emission benefits were demonstrated with the Mossgas fuel. NOx was reduced by 12 - 18% across the three different transient cycles employed, while particulate matter (PM) was reduced by an even greater 25 - 50%. This bus represents currently prevailing emissions certification standards, and demonstrates the emission reduction benefits of the Mossgas diesel even for relatively low emitting four stroke engines.

The Mossgas synthetic diesel was independently tested and reported on in an SAE paper (SAE paper 1999-01-1512) [4] produced by the National Renewable Energy Laboratory, West Virginia University and the U.S.

Department of Energy, "Emissions from Buses with DDC 6V92 Engines using Synthetic Diesel Fuel." The following was reported:

- For each of the buses tested, the fuel consumption (Btu/mile) was not strongly affected by the fuel type. This was when the Mossgas synthetic diesel was compared to the Federal no. 2 diesel.
- Use of Mossgas synthetic diesel in place of Federal no. 2 diesel in test buses led to lower levels of all four regulated emissions measured. For the buses with rebuilt engines and oxidation catalytic converters, oxides of nitrogen were reduced by an average of 8%, particulate matter was reduced by an average of 31%, carbon monoxide was reduced by an average of 35% and total hydrocarbon emissions were reduced by an average of 49%.
- Drivers could not detect a performance difference between buses operating on the Mossgas synthetic diesel and the Federal no. 2 diesel over the CBD driving cycle.
- The use of Mossgas synthetic diesel fuel and the use of rebuilt engines and catalysts according to the EPA Urban Bus Retrofit/Rebuild Program both show promise for reducing emissions from older transit buses using Detroit Diesel 6V92 engines.

EMISSION TESTING AT WEST VIRGINIA UNIVERSITY – ENVIRONMENTAL BENEFITS

The emissions reduction potential of Mossgas zero sulphur, natural gas-derived diesel fuels was determined in a series of engine dynamometer and heavy duty chassis dynamometer tests that were conducted in early 1999 by West Virginia University's Engine and Emissions Research Center [5]. Four sets of full emissions measurement tests were conducted, namely

1) Transient engine dynamometer testing on a 1998 Navistar T444 diesel engine (typical of medium heavy duty truck engines in use today) over the Federal Test Procedure (FTP), as used for engine certification in the United States,

2) Transient engine dynamometer testing on a 1992-specification Detroit Diesel Corporation 6V-92 two stroke-cycle engine (typical of engines in use in 1990-1998 era transit buses) over the Federal Test Procedure (FTP),

3) Transient chassis dynamometer testing on two 40-foot transit buses with Detroit Diesel Corporation 6V-92 engines (owned by the Port Authority of Allegheny County, Pittsburgh, Pa.) over the Central Business District Cycle. One bus was typical of an in-use unmodified bus, while the other bus had been remanufactured to 1998 EPA Urban Bus Retrofit Standards, and

4) Transient chassis dynamometer testing on a 1999-specification 40-foot transit bus with a Detroit Diesel Corporation Series 50 four stroke-cycle engine (owned by the New York City Transit Authority,

New York, NY). This bus was tested over several different transient heavy-duty chassis dynamometer test cycles.

This comprehensive emissions study, the largest of its type conducted to date, was designed to include

- Both heavy-duty engine dynamometer and vehicle dynamometer transient emissions testing,
- Both two and four stroke cycle heavy-duty engines from two different engine manufacturers,
- A range of engine technologies and ages,
- A range of transient chassis dynamometer test cycles, and
- The effect of catalytic exhaust gas aftertreatment on engine emissions using these fuels.

Several fuels were used in this study, including conventional Regular 49-state number 2 diesel fuel as the baseline (D2), the Mossgas synthetic, zero sulphur natural gas-derived fuel (RFD 1), a oxygenated blend of Mossgas RFD fuel (RFD 3), and a proprietary synthetic zero sulphur diesel fuel (COD syndiesel – MG COD). The COD syndiesel constitutes at least 60% of the Mossgas RFD fuels.

Table 4: Fuel Specifications

	UNITS	D2
Density at 20C	kg/l	
Distillation		
90%(v/v) recovery	C	306
F.B.P	C	331
Total sulphur	wt%	0.035
Cetane number		48.7
Aromatic content	% v/v	24.7

Engine and Vehicle Exhaust Emissions Testing

Engine exhaust emissions, including unburned hydrocarbons (HC), carbon monoxide (CO), carbon dioxide (CO_2), oxides of nitrogen (NOx) and particulate matter (PM), were measured with a 400 kW GE transient engine dynamometer. A full-scale dilution tunnel system meeting the United States Code of Federal Regulations (CFR 40) requirements to perform engine certification was used. The equipment and procedures used for in this laboratory are as required in CFR 40 Part 86, Subpart N. Similar equipment is used for the heavy duty vehicle chassis dynamometer.

Table 5: Engines used in Engine Dynamometer Testing

Manufacturer	Model	Power Rating	Configuration	Control
Navistar	T444E 1998	230 hp at 2200 rpm	V8, turbocharged, intercooled, direct injection, 4 stroke	Electronic EEC-IV (injection timing and injection pressure control)
Detroit Diesel Corporation (DDC)	6V-92TA 1992	253 hp at 2100 rpm 880 ft.lb@1200rpm	V6, turbocharged, intercooled, direct injection, 2 stroke	Electronic DDEC-II (injection timing control)

Engines used were unmodified, and injection timing modifications could probably be used to obtain significantly lower PM emissions for the same NOx emission levels, or vice versa.

Table 6: Engine Dynamometer FTP Transient Emissions Results for 1998 Navistar T444E

	HC (g/bhp.hr)	CO (g/bhp.hr)	CO_2 (g/bhp.hr)	NOx (g/bhp.hr)	PM (g/bhp.hr)
D2	0.183	1.091	669.81	3.848	0.112
RFD 1	0.169 (-7.8%)	0.890 (-18.5%)	647.37 (-3.4%)	3.459 (-10.1%)	0.096 (-14.8%)
RFD 3	0.327 (+78%)	1.016 (-6.9%)	643.38 (-3.9%)	3.339 (-13.2%)	0.096 (-14.3%)

Table 7: Engine Dynamometer FTP Transient Emissions Results for 1992 DDC 6V-92TA

	HC (g/bhp.hr)	CO (g/bhp.hr)	CO_2 (g/bhp.hr)	NOx (g/bhp.hr)	PM (g/bhp.hr)
D2	0.50	1.60	723.65	4.97	0.24
MG COD	0.50 (0.0%)	0.94 (-41.1%)	695.94 (-3.8%)	4.77 (-4.0%)	0.20 (-14.5%)
D2	0.67	1.58	726.38	5.00	0.24
RFD 1	0.59 (-12.3%)	1.32 (-16.4%)	699.95 (-3.6%)	4.93 (-1.4%)	0.20 (-15.5%)

Table 8: Transient Chassis Dynamometer Testing over the Central Business District Cycle – Transit Bus Testing – Port Authority of Allegheny County

			Emissions Results (g/mile)					Fuel Economy	
Unmodified Bus#1	Cycle	Fuel	HC	CO	CO_2	NOx	PM	Mile/ Gal	BTU/ mile
	CBD	D2	1.02	39.4	5059	27.5	10.0	1.99	65456
	CBD	RFD 1	0.90	32.5	4908	26.5	8.86	1.86	66365
	CBD	RFD 3 (5% Mosstanol)	0.96	21.8	5034	26.9	7.45	1.82	67820
	CBD	D2	1.33	39.9	4896	26.3	8.93	2.05	63398
	CBD	RFD 1	1.07	33.2	4771	24.8	8.56	1.91	64549
	%Reduction RFD 1over D2		-16.2	-17.2	-2.8	-4.7	-8.0		
	%Reduction RFD 3 over D2		-18.3	-45.0	1.1	0.0	-21.3		
Catalytic Converter Equipped Bus#2	CBD	D2	0.43	1.72	4356	26.8	1.69	2.33	55705
	CBD	RFD 1	0.40	0.38	4347	25.2	1.27	2.12	58157
	CBD	RFD 3 (5% Mosstanol)	0.42	0.27	4367	26.6	0.97	2.11	58424
	CBD	D2	0.35	1.07	4458	26.9	1.89	2.28	56995
	%Reduction RFD 1 over D2		2.6	-72.8	-1.4	-6.2	-29.1		
	%Reduction RFD 3 over D2		7.7	-80.7	-0.9	-0.9	-45.8		

Table 9: Transient Chassis Dynamometer Testing over 3 different transient driving cycles– Transit Bus Testing – New York City Transit Authority

Fuel	Cycle	HC g/bhp.hr	CO g/bhp.hr	CO_2 g/bhp.hr	NOx g/bhp.hr	PM g/bhp.hr	Mile/ Gal	BTU/ mile
Diesel	CBD	0.05	2.09	2869	36.7	0.150	3.39	37579
COD syndiesel	CBD	0.05	1.03	2816	32.2	0.085	3.28	37684
	% Reduction COD over D2	0.0	-54.6	-0.7	-12.7	-43.3		
Diesel	NY Bus	0.12	15.50	7639	85.7	0.730	1.26	100162
COD syndiesel	NY Bus	0.15	6.55	7272	72.3	0.370	1.27	97399
	%Reduction COD over D2	25.0	-57.7	-4.8	-15.6	-49.3		
Diesel	Route 22	0.10	2.60	2506	32.9	0.130	3.84	32809
COD syndiesel	Route 22	0.15	1.96	2386	26.9	0.097	3.87	31952
	%Reduction COD over D2	50.0	-24.6	-4.8	-18.2	-25.4		

NOTES:

CBD: Central Business District Cycle

NY Bus: New York City Bus Cycle

Route 22: A driving cycle developed from actual in-use bus testing in NY City.

Emission Testing Conclusions

It has been shown that there are significant emissions reduction benefits to be obtained from the use of zero sulfur, low aromatic, relatively high cetane number distillate fuels with or without the use of oxygenates.

The following specific conclusions can be drawn from the engine and vehicle exhaust emissions testing performed, namely

- In a modern medium heavy-duty four-stroke cycle diesel engine (1998 Navistar T444E), reductions of 10-13% in NOx and up to 15% in PM were obtained using RFD and 5% Mosstanol in RFD, with no deleterious effects in the other emissions levels (HC and CO emissions remain well below regulated levels). It should be borne in mind that the engine used was unmodified, and that injection timing modifications could probably be used to obtain significantly lower PM emissions for the same overall NOx emissions levels, or vice versa. This testing shows that there is a significant potential for the use of a mildly oxygenated, zero sulfur, moderate cetane number diesel fuel in modern four-stroke heavy-duty truck engines.

- In a heavy-duty, two-stroke cycle diesel engine (1992 DDC 6V-92TA), similar simultaneous reductions in NOx (1-2%) and PM (up to 15%) were achieved, showing the benefit of either neat RFD or the RFD 3 blend in reducing the emissions from an unmodified 2-stroke engine used in transit bus application. Similar PM reductions were seen using the COD fuel, leading to the conclusion that the zero sulphur fuel specification leads to similar reductions in PM regardless of engine technology, as this trend was noted for both 2- and 4- stroke cycle engines.

EMISSION STANDARDS FOR HEAVY ENGINES

In the absence of emission standards for heavy-duty vehicles such as transit buses it can be concluded that the Mossgas RFD fuels reduce emissions significantly in current technology engines and that these fuels show significant promise in their use in engines with sulfur-sensitive aftertreatment devices.

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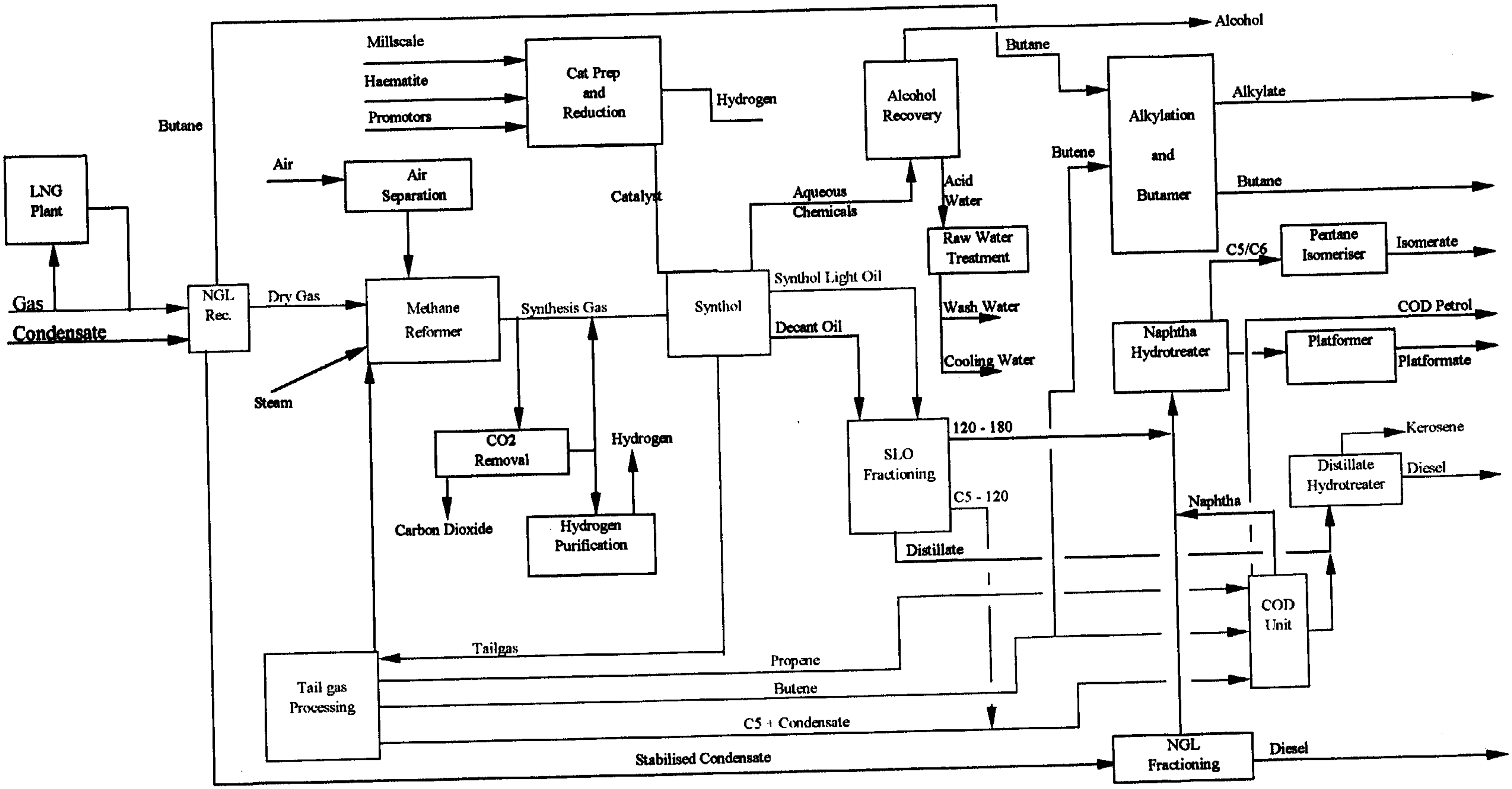
DEFINITIONS, ACRONYMS, ABBREVIATIONS

CEF	-	Central Energy Fund (Pty) Limited of South Africa
CBD	-	Central Business District (driving cycle)
CO	-	Carbon Monoxide
COD	-	Conversion of Olefins to Distillate
DDC	-	Detroit Diesel Corporation
DOE	-	U.S. Department of Energy
EPA	-	Environmental Protection Agency
FBP	-	Final Boiling Point
F-T	-	Fischer-Tropsch
FTP	-	Federal Test Procedure
GTL	-	Gas to Liquids
HC	-	Hydrocarbons
HFRR	-	High Frequency Reciprocating Rig
IBP	-	Initial Boiling Point
MG	-	Mossgas
NOx	-	Oxides of Nitrogen
NREL	-	National Renewable energy Laboratory
PM	-	Particulate Matter
RFD	-	Reformulated Diesel
WVU	-	West Virginia University

FIGURE 1 - MOSSGAS FLOW DIAGRAM



WEST VIRGINIA UNIVERSITY

Department of
Mechanical and Aerospace Engineering

TRANSIENT EMISSIONS TESTING OF A REFORMULATED FISCHER-TROPSCH DIESEL FUEL IN HEAVY-DUTY DIESEL ENGINES

<u>Submitted to</u>

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May 13, 1999

Contents

1. Introduction

In order to measure the emissions reduction potential of Mossgas' zero sulphur, natural gas-derived diesel fuels, a series of engine dynamometer and heavy duty chassis dynamometer tests were conducted. Four sets of full emissions measurement tests were conducted, namely

1) Transient engine dynamometer testing on a 1998 Navistar T444 diesel engine (typical of heavy duty truck engines in use today) over the Federal Test Procedure (FTP),
2) Transient engine dynamometer testing on a 1992-specification Detroit Diesel Corporation 6V-92 engine (typical of engines in use in 1990-1998 era transit buses) over the Federal Test Procedure (FTP),
3) Transient chassis dynamometer testing on two 40-foot transit buses with Detroit Diesel Corporation 6V-92 engines (Port Authority of Allegheny County, Pittsburgh, Pa.) over the Central Business District Cycle (one bus typical of an in-use unmodified bus, and the other typical of a bus remanufactured to 1998 EPA Urban Bus Retrofit Standards), and
4) Transient chassis dynamometer testing on one 40-foot transit bus with a Detroit Diesel Corporation Series 50 engine (New York City Transit Authority, New York, NY) over several different transient test cycles.

As a result, the testing described in this report was designed to include

- Both engine dynamometer and vehicle dynamometer transient emissions testing,
- Both 2 and 4 stroke cycle heavy-duty engines from two different engine manufacturers,
- A range of engine technologies and vintages,
- A range of transient chassis test cycles,
- Several fuels, including conventional, synthetic, Fischer-Tropsch and oxygenated FT fuels, and
- The effect of exhaust gas aftertreatment on engine emissions using these fuels.

2. Fuels Used

The fuels used and their acronyms are:

- Regular Federal 49-state number 2 diesel fuel (British Petroleum) – D2
- Regular Federal 49-state number 1 diesel fuel – D1
- Reformulated Diesel Fuel (Mossgas) – RFD
- Low Aromatic Distillate (Mossgas) – Conversion of Olefins to Diesel – MG
- Mosstanol 120 (Mossgas) – alcohol mixture (used as an oxygenate) – M or MOL

Note for example that MG50 refers to a 50%-50% blend of MG and D2, and RFD95/M5 is a 95% RFD, 5% Mosstanol blend.

An analysis of each of the fuels used is given below.

Analysis	UNITS	ASTM	RFD	MG
Color	ASTM	D1500	L1.0	0.5
Appearance		Caltex Haze Test	1	1
Density at 20C	kg/l	D-4052	0.8055	0.8007
Distillation		D-86		
90%(v/v) recovery	C		319.8	321.1
F.B.P	C		>365	360.8
Flash Point	C	D-93	95	100
Kin. Viscosity @ 40C	cSt	D-445	2.710	2.974
Cold Filter Plugging Point	C	IP309		
October to March			-15	<-36
April to September				
Cloud Point	C	D-2550		
Ash	wt%	D-482		<0.01
Sediment by Extraction	wt%	D-473		<0.01
Water content	% v/v	D-1744	0.006	0.01
Carbon residue, Rams (on 10% residue)	wt%	D-4530	0.10	0.09
Total sulphur	wt%	D-2622	<0.001	<0.001
Copper Corrosion (3h @ 100C)	Rating	D-130	1A	1A
Strong acid number	mg KOH/g	D-974	NIL	NIL
Acid number	mg KOH/g	D-974	0.02	0.013
Cetane number		D-613	53.3	51.4
Conductivity @ 15C	pS/m	D-2624	160	
Aromatic content	% v/v	D-1391	16.9	10.1
Oxidation stability	mg/100 ml	D-2274	0.2	0.3

Analysis	UNITS	ASTM	D2
Aromatic Saturates	% v/v % v/v	D-1391 D-1391	24.7 73.8
Olefins	% v/v	D-1391	1.5
Distillation		D-86	
Initial Boiling Pt.	F		370
5%	F		398
10%	F		414
20%	F		434
30%	F		456
40%	F		475
50%	F		492
60%	F		510
70%	F		530
80%	F		552
90%	F		584
95%	F		606
F.B.P	F		628
Recovery	% vol		98.5
Residue	% vol		1.5
Loss	% vol		0
Carbon/Hydrogen	Mass%	D-5291	
Carbon			86.11
Hydrogen			13.37
Nitrogen			<0.03
API Gravity @ 60F	API	D-287	37.4
Cetane index (Calc.)		D-976	48.7
Heat of Combustion		D-240	
Gross Heat Value	BTU/gal		137609
Net Heat Value	BTU/gal		129147
Gross Heat Value	BTU/lb		19726
Net Heat Value	BTU/lb		18513

Combustion-related Properties	Units	ASTM Test	MG	D2
Carbon/Hydrogen	mass%	D5291		
Carbon			83.98	86.11
Hydrogen			14.43	13.37
Nitrogen				<0.03
Residual				
Oxygen (by diff)			1.59	
Heat of Combustion		D240		
Gross	Btu/gal		134,712	137,609
Net			125,878	129,147

Table 1: Fuel Specifications

Year	HC	CO	NOx	PM
Heavy Duty Diesel Truck Engines				
1990	1.3	15.5	6.0	0.60
1991	1.3	15.5	5.0	0.25
1994	1.3	15.5	5.0	0.10
1998	1.3	15.5	4.0	0.10
Urban Bus Engines				
1991	1.3	15.5	5.0	0.25
1993	1.3	15.5	5.0	0.10
1994	1.3	15.5	5.0	0.07
1996	1.3	15.5	5.0	0.05
1998	1.3	15.5	4.0	0.05

Table 2: EPA Emissions Standards for Heavy Duty Diesel Engines (g/bhp.hr)

Note that only HD engines are certified to the above standards; there are no heavy-duty vehicle in-use standards at present.

3. Engine Testing Procedures

The Engine and Emissions Research Center (EERC) at WVU is equipped with state-of-the-art engine test equipment and is capable of operating light and heavy duty engines over both transient and steady state cycles. The EERC is equipped with a 550 hp DC dynamometer that occupies one of the two main test beds in the engine cell while a new AC engine dynamometer is being installed to perform medium and heavy duty engine and emissions research. The EERC also performs development research using an additional eddy current and water brake dynamometers. Emissions are measured using a full scale dilution tunnel system meeting the Code of Federal Regulations (CFR 40) requirements to perform engine certification. The equipment and procedures used for in this laboratory are as required in CFR 40 Part 86, Subpart N; similar equipment is used in the EERC is used by the WVU transportable laboratory.

Engine exhaust is ducted to a full scale dilution tunnel (18 inches in diameter and 20 feet in length) based on the critical flow venturi-constant volume sampler (CFV-CVS) concept. The tunnel employs an orifice of 8 inches placed 3 feet from the beginning of the tunnel which ensures that the dilute exhaust is thoroughly mixed by the time it reaches the sampling zone, ten diameters downstream of the orifice. The quantity of dilute exhaust is measured precisely using critical orifices. The critical flow venturis, located upstream of the dilution blower, operate under sonic (or choked) condition which fixes the dilute exhaust mass flow rate. The tunnel has selectable flow rates of 400, 1000, 1500, 2000, 2500, and 3000 scfm, depending on the size of the engine and the dilution rate required. Conditioned air is supplied to the test cell where is serves as both engine intake air and dilution air. Heated sampling probes and lines transfer dilute exhaust to exhaust gas analyzers outside the test cell.

Continuous sampling and analysis of the exhaust stream is done by non-dispersive infrared analyzers (NDIR) for carbon monoxide (low and high) and carbon dioxide; chemiluminescent detection (CLD) for oxides of nitrogen and heated flame ionization detector (HFID) for total hydrocarbons. The gas analysis bench is equipped with exhaust sample conditioning and analysis systems as per EPA, CFR 40 requirements. Data from the exhaust analyzers, sampling trains and the double dilution tunnel, and the engine are acquired and archived at 5 Hz.

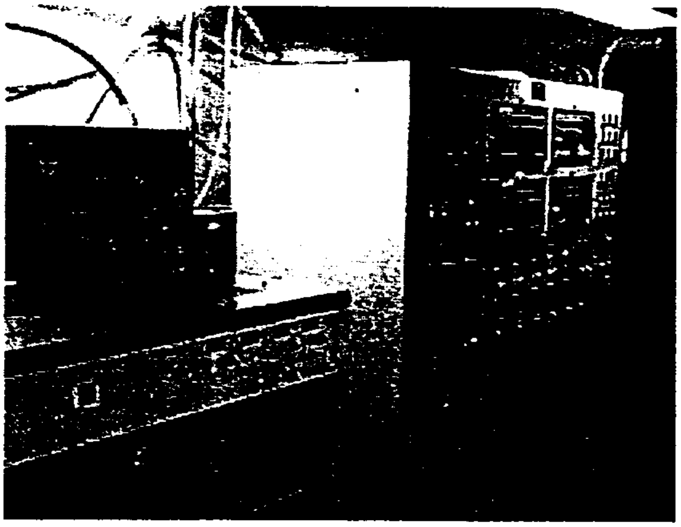


Figure 1 - Gaseous emissions analyzer bench.

Table 3 - Gaseous and particulate emissions analyzers used at the WVU EERC.

Exhaust Emission Component	Acronym	Method	Manufacturer	Model
Carbon Monoxide	CO	NDIR	Rosemount Analytical	880A
Hydrocarbons	HC	HFID	Rosemount Analytical	402
Oxides of Nitrogen	NOx	CLD	Rosemount Analytical	955
Carbon Dioxide	CO_2	NDIR	Beckman Industrial	868
Particulate Matter	PM	TEOM	Rupprecht & Patashnik	1105

Total particulate matter is measured using 70-mm fluorocarbon coated glass fiber filters for subsequent gravimetric analysis. An environmental chamber (maintained at 70°F and 50% RH) and a Cahn microbalance are part of the particulate matter sampling and analysis system. Continuous particulate matter (PM) is also measured using a tapered element oscillating microbalance (TEOM) device, developed by Rupprecht & Patashnik. Integrated TEOM results and 70-mm filter data are routinely compared to ensure data integrity.

Table 4 - Engines used in Engine Dynamometer Testing

Manufacturer	Model	Power Rating	Configuration	Control
Navistar	T444E	230 hp at 2200 rpm	V8, turbocharged, intercooled, direct injection, 4 stroke	Electronic EEC-IV (injection timing and injection pressure control)
Detroit Diesel Corporation (DDC)	6V-92TA	253 hp at 2100 rpm 880 ft.lb@1200rpm	V6, turbocharged, intercooled, direct injection, 2 stroke	Electronic DDEC-II (injection timing control)

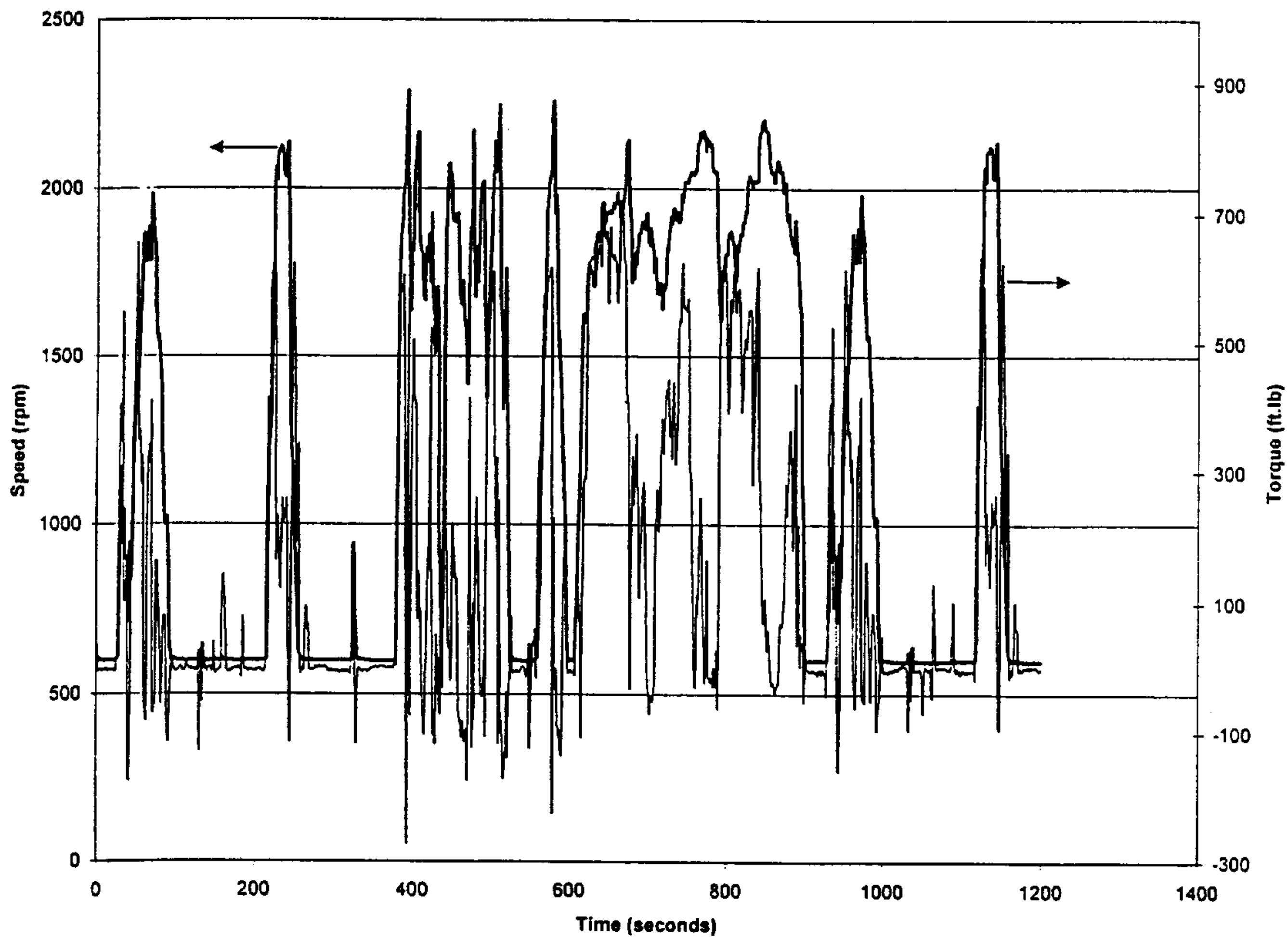


Figure 2: Federal Test Procedure (FTP) for Heavy Duty Engine Testing and Certification (speed [upper trace] and load [lower trace] versus time).

The engine testing emissions results on the fuels tested are given in Section 5.1 for the Navistar T444E engine, and in Section 5.2 for the DDC 6V-92TA engine.

4. Chassis Testing Procedures

Transit Bus Testing – Pittsburgh DDC 6V-92

Two 1991 Orion 40-foot transit buses (operated by the Port Authority of Allegheny County, Pittsburgh, Pennsylvania) were tested using D2, and RFD. These buses were fitted with Detroit Diesel Corporation 6V-92 TA heavy-duty two-stroke diesel engines (with the DDEC-II engine control system), employing direct injection with electronic unit injectors. These engines are 2-stroke, vee-configuration, 6 cylinder, 9.05 liter turbocharged and aftercooled and are representative of engines in transit bus use in the US (with approximately 30,000 of these engines in use in transit fleets today).

One of the buses used in this study had an engine with high mileage accumulation (over 350,000 miles) and was not equipped with exhaust gas aftertreatment. The other bus had an engine that was recently rebuilt according to the Environmental Protection Agency's Urban Bus Retrofit/Rebuild Program and was fitted with an oxidation catalytic converter manufactured by Engine Control Systems Ltd. The test buses were not modified in any way for the Mossgas synthetic diesel fuel.

The vehicles were operated through the Central Business District driving schedule (shown in Figure 8) while vehicle emissions, axle torque, and speed were monitored and recorded. Emissions monitored during the testing included hydrocarbons (HC), carbon monoxide (CO), carbon dioxide (CO_2), oxides of nitrogen (NO_X), and total particulate matter (PM). In addition, a sample of diesel fueled vehicles was also tested to provide baseline emissions data for comparative purposes. The results for this testing are shown in Section 5.3.

Transit Bus Testing – New York City DDC Series 50

The opportunity arose to test a 1999 model year 40 foot transit bus (made by TMC), using a four stroke Detroit Diesel Corporation Series 50 direct injection engine, certified to 1998 transit bus emissions standards (8.5 liter, 275 hp). This would allow the comparison of older two-stroke bus engine technology (representative of the large installed base of transit vehicles) to newer 4 stroke bus engine technology. The New York City Transit Authority (NYCTA) bus was tested over the CBD cycle (shown in Figure 8) as well as the New York City Bus Cycle (Figure 9) and a newly developed cycle termed Route 22 (Figure 10). The latter cycle was developed from real-world, in-use transit bus activity data by MJ Bradley and Associates. The results for this testing are shown in Section 5.4.

WVU Transportable Chassis Dynamometer Test Laboratory

The WVU Transportable Heavy Duty Emissions Testing Laboratory tests alternatively fueled vehicles across North America in cooperation with the United States Department of Energy, Office of Transportation Technologies. The main objective of the program is to build an emissions database that can be used to ascertain emissions performance and fuel efficiency of alternatively fueled vehicles. The University designed, constructed and now operates two Transportable Heavy Duty Vehicle Emissions Testing Laboratories which travel to transit agencies and trucking facilities where the laboratory is stationed to test vehicle emissions. Detailed information pertaining to the Transportable Laboratory can be found at through the Internet at the following web sites:

NREL database (Heavy-duty truck program)	http://www.afdc.nrel.gov/web_view/emishdv.html
NREL database (Transit bus program)	http://www.afdc.nrel.gov/web_view/emisbus.html
USDOE OTT	http://www.ott.doe.gov/
WVU Transportable Laboratory	http://www.cemr.wvu.edu/~wwwatf/TransportableLaboratory.html

Several technical papers (SAE 961082, SAE 951016, and SAE 952746) have been presented on the design of the two laboratories and on emissions data collected from both conventional and alternatively fueled vehicles.

Each laboratory consists of a dynamometer test bed, instrumentation trailer and support trailer. The test bed (Figures 3, 4 and 5) is designed such that it can be transported to the test site by a tractor truck where it is can then be lowered to the ground. Once lowered, subject vehicles can then be driven on to the test bed. Before a vehicle is mounted onto the test bed, the outer drive wheels of the vehicle are removed and replaced by special adapters (Figure 6). This provides a connection to transmit power between the drive axle of the vehicle and the dynamometer. Each dynamometer unit consists of speed-increasing gearboxes with a power absorber and a flywheel set. The flywheel sets consist of a series of selectable discs used to simulate vehicle inertia. During the test cycle, torque cells and speed transducers at the vehicle hubs monitor wheel torque and hub speed.

Figure 3 - Heavy-duty Vehicle Emissions Testing Laboratory #1

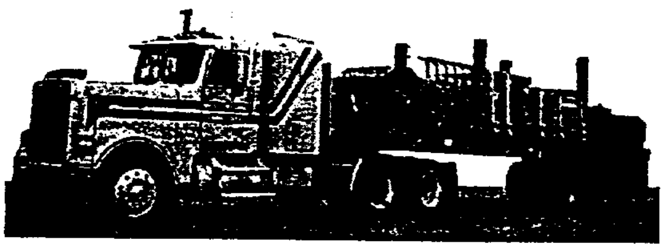


Figure 4 - Dynamometer test bed packed for transport

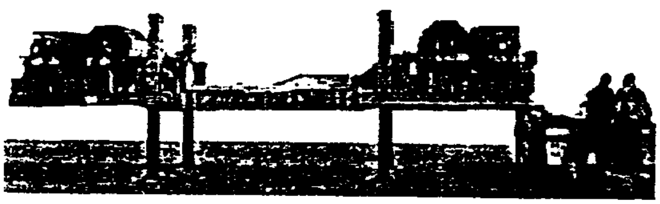


Figure 5 - Test bed ready for lowering in preparation for testing

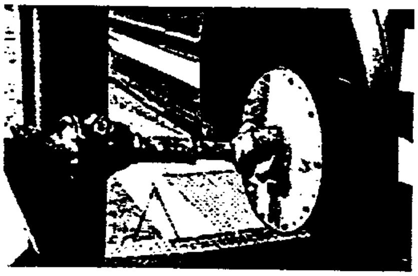


Figure 6 - Close-up view of adapter connecting the vehicle hub to the dynamometer drivetrain

The instrumentation trailer (Figure 7) holds both the emissions measurement system for the laboratory and the data acquisition and control hardware necessary for the operation of the test bed. Exhaust emissions from the subject vehicle are piped to a 45cm dilution tunnel integrated into the instrumentation trailer. The tunnel mixes the exhaust with ambient air which both cools and dilutes the exhaust. Dilution tunnel flow control is realized using a critical flow venturi system (CVS). A two-stage blower system maintains critical flow through various sized venturi throat restrictions to maintain a constant mass flow of dilute exhaust during testing.

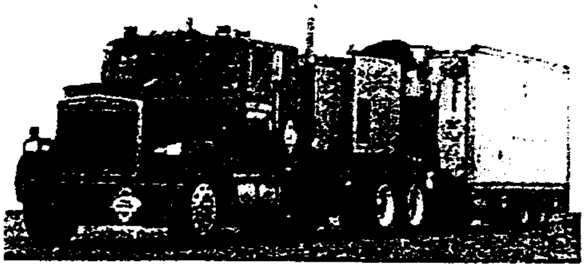


Figure 7 - Instrumentation trailer and transport vehicle

Dilute exhaust samples are drawn from sample probes located 4.5m from the mouth of the dilution tunnel. The samples are routed to the respective analyzers using heated sampling lines. Levels of carbon dioxide (CO_2), carbon monoxide (CO), oxides of nitrogen (NO_x) and hydrocarbons (HC) are measured continuously, then integrated over the complete test cycle. A sample of the ambient air is collected in a Tedlar bag and analyzed at the end of each test. These measurements are then subtracted from the continuous measurements.

A gravimetric measurement of particulate matter (PM) is obtained using 70mm filters, weighed before and after testing. The filters are conditioned for temperature and humidity in an environmental chamber before each weighing to reduce error due to variation in water content. Non-Methane Hydrocarbon (NMHC) levels in the exhaust were determined using gas chromatography. Samples of the dilute exhaust are sent back to WVU for analysis with a Varian 3600 model gas chromatograph which can determine the volume concentration of methane as well as other volatile hydrocarbons.

The buses in this project were tested using a modified form of the Central Business District (CBD) cycle. This speed-time cycle, shown in Figure 8, contains 14 identical test sections, each containing an acceleration from idle to 20 mph followed by a steady state cruise section and a deceleration to idle. The NY City Bus Cycle and the new Route 22 bus cycle (Figures 9 and 10) were also used during the chassis dynamometer testing.

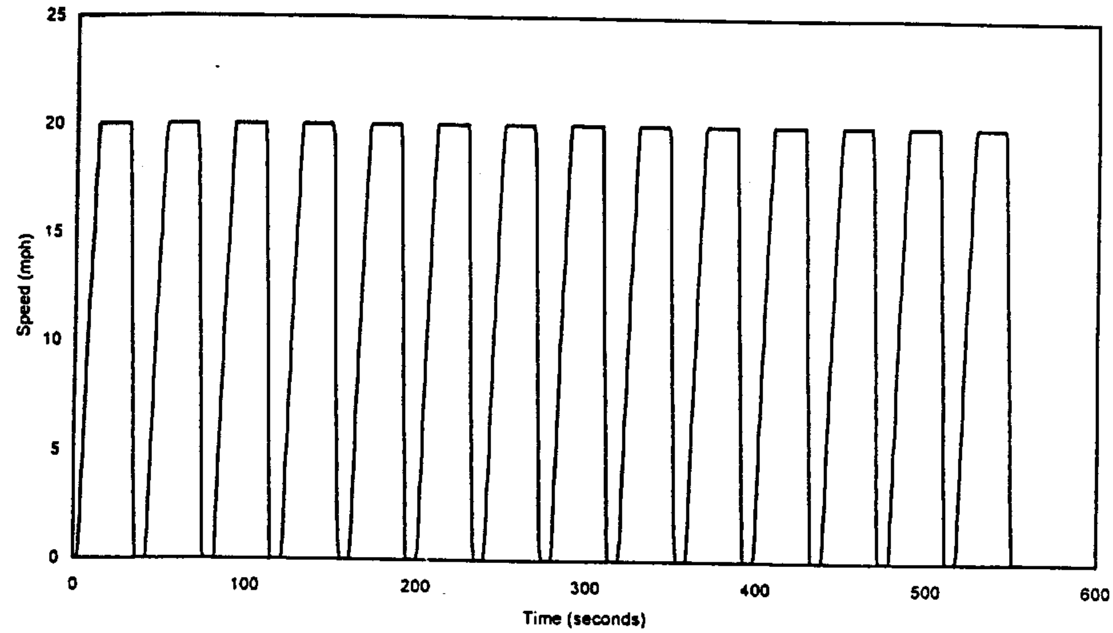


Figure 8 – Central Business District Cycle (CBD) used for measuring the emissions from heavy duty Transit Buses.

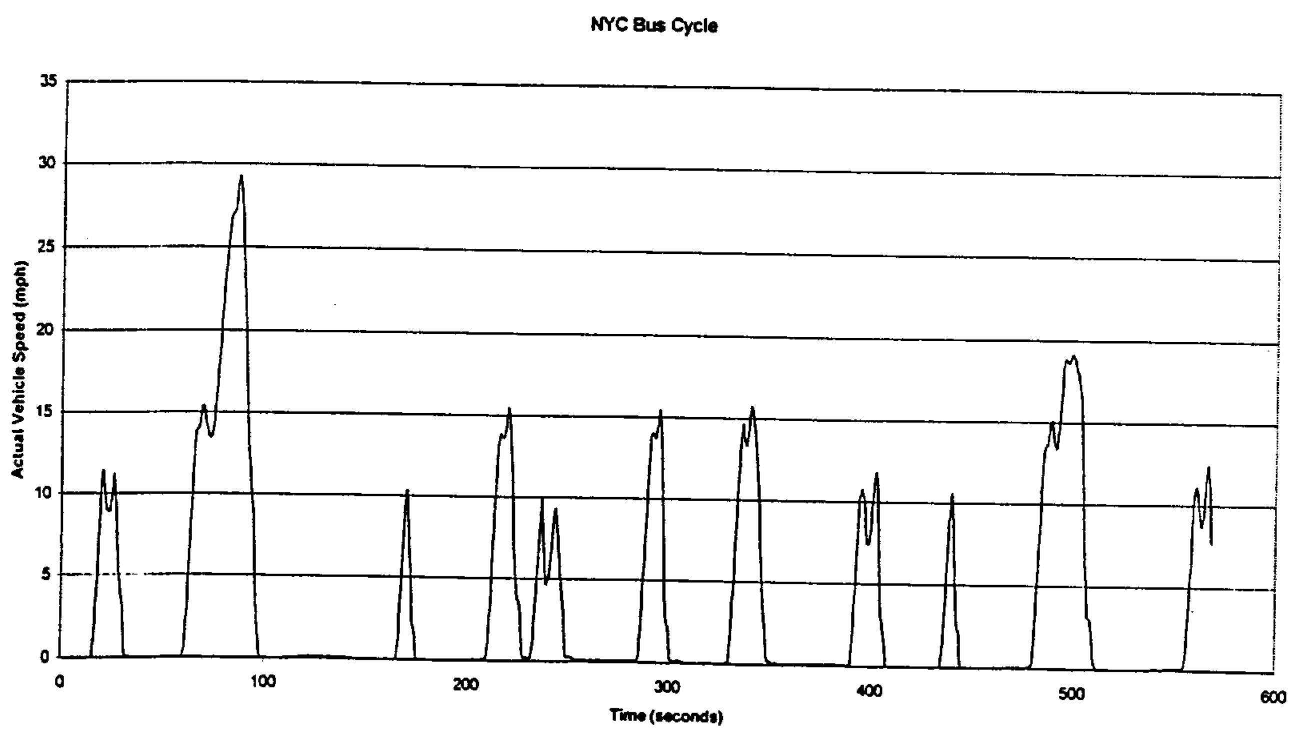


Figure 9 – New York City Bus Cycle used for measuring the emissions from transit buses. (Note the fairly significant amount of idle time, which tends to increase the vehicle emissions in terms of mass emitted per unit distance.)

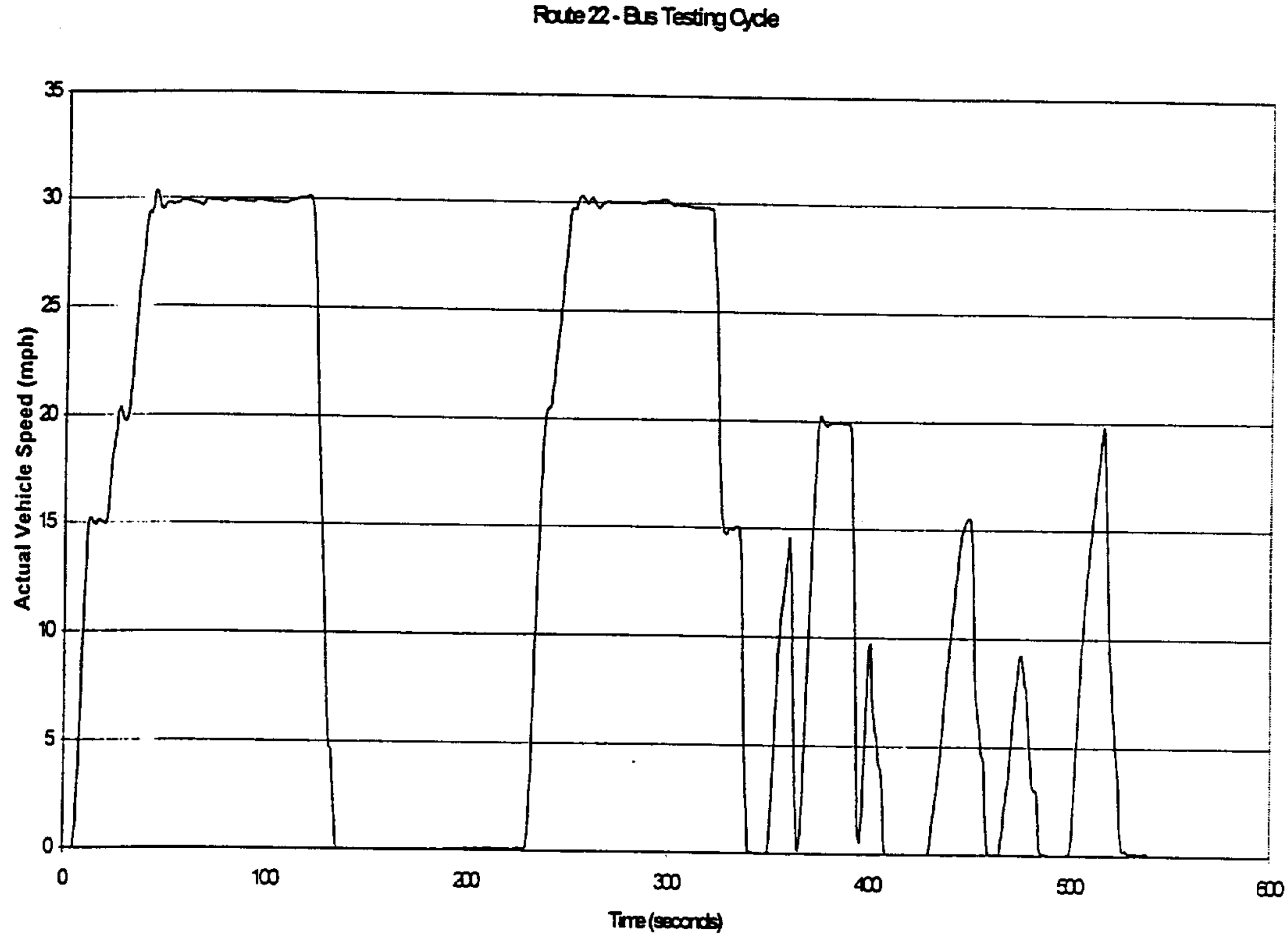


Figure 10 – Route 22 transit bus testing cycle, developed by MJ Bradley and Associates from real-world bus activity data gathered in New York City.

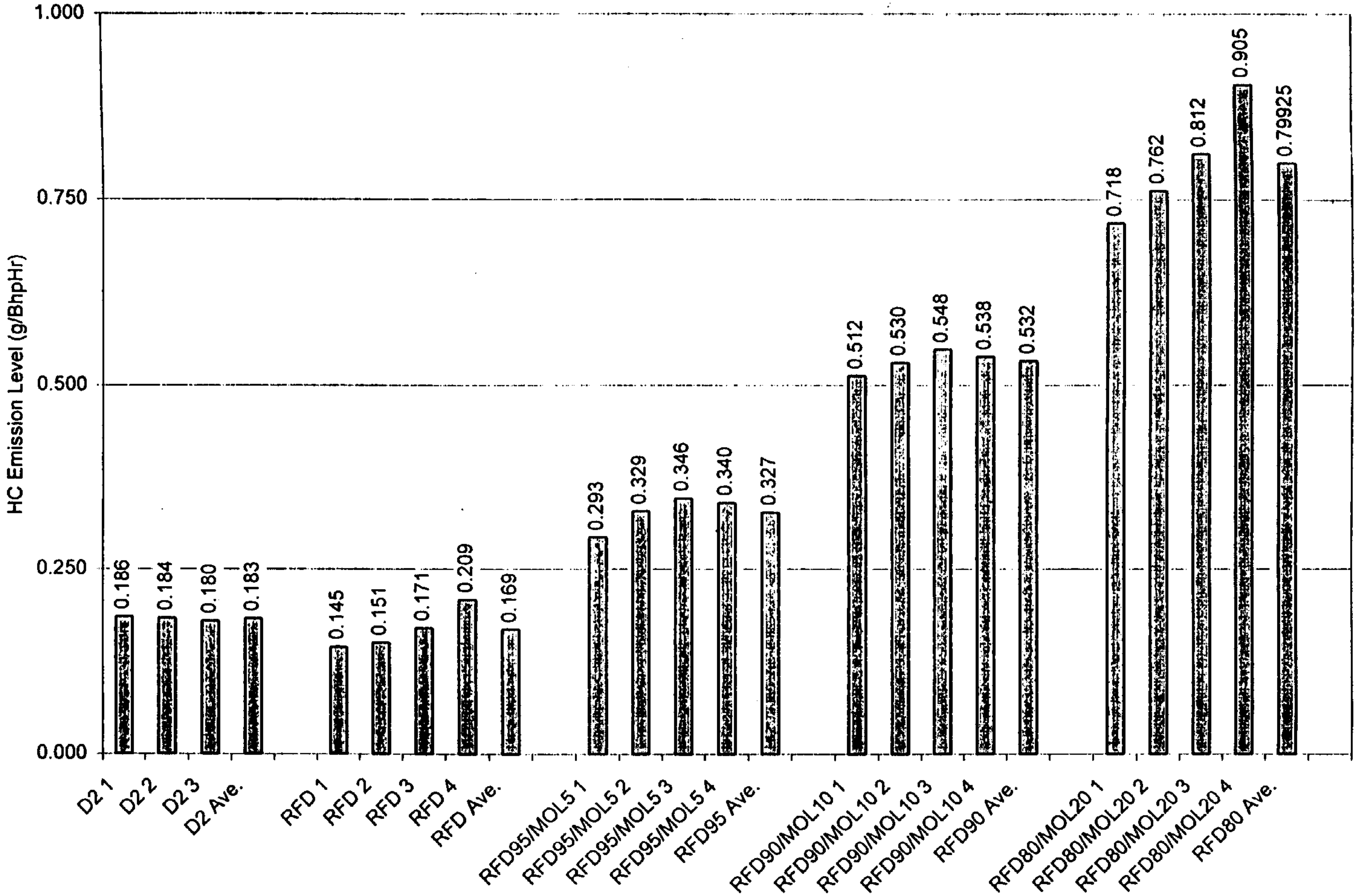
5 Emissions Results and Comparisons

5.1 Transient Engine Testing over the FTP – Navistar T444E

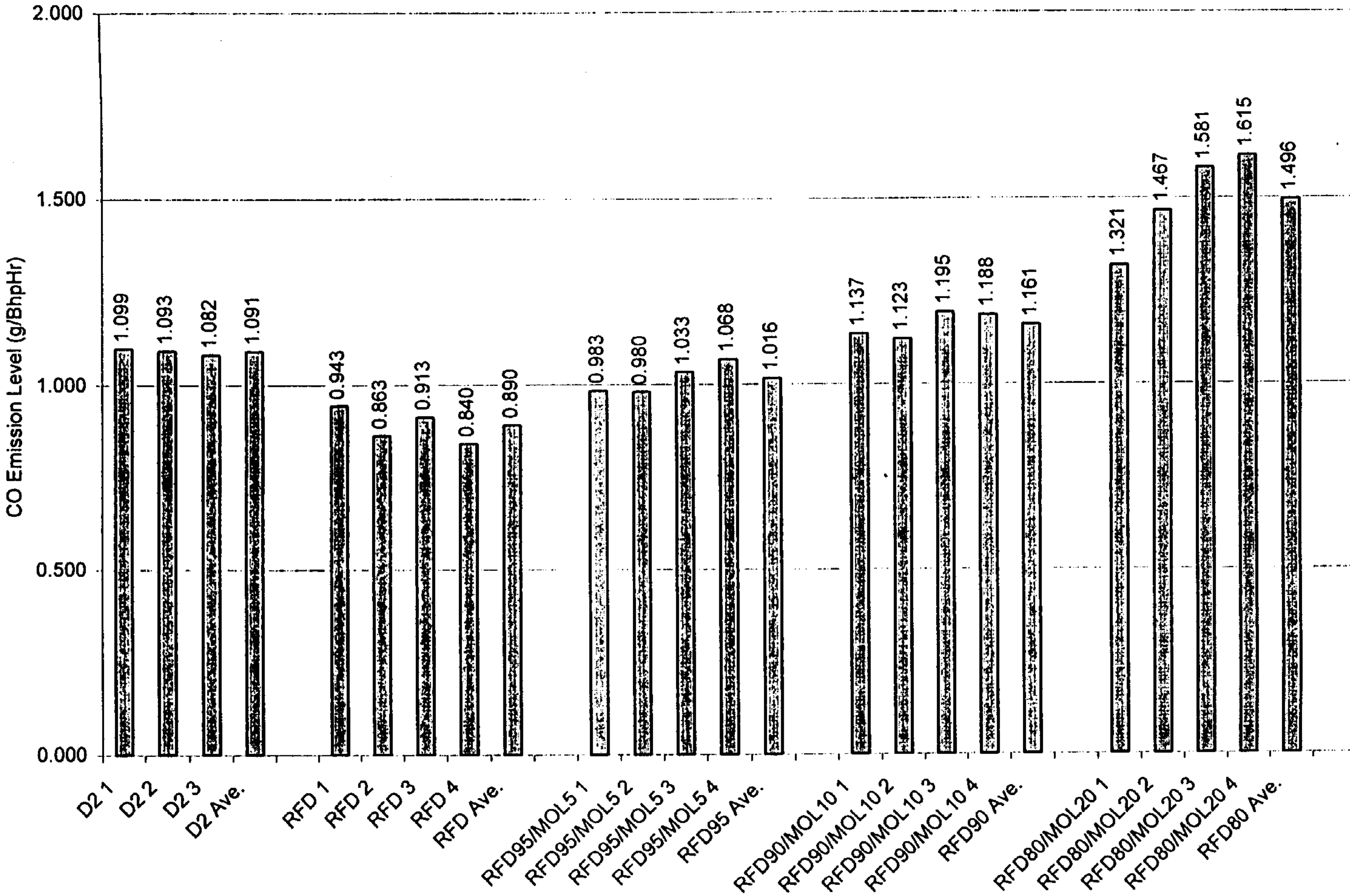
	Test		HC	CO	CO2	NOx	PM
			g/bhphr	g/bhphr	g/bhphr	g/bhphr	g/bhphr
Pump D2	FTP01	D2 1	0.186	1.099	673.0	3.835	0.113
	FTP02	D2 2	0.184	1.093	668.4	3.841	0.112
	FTP03	D2 3	0.180	1.082	668.1	3.867	0.112
Average		D2 Ave.	0.183	1.091	669.817	3.848	0.112
Mossgas RFD	FTP04	RFD 1	0.145	0.943	654.4	3.549	0.102
	FTP05	RFD 2	0.151	0.863	648.3	3.460	0.095
	FTP06	RFD 3	0.171	0.913	643.4	3.418	0.094
	FTP07	RFD 4	0.209	0.840	643.4	3.409	0.092
Average		RFD Ave.	0.169	0.890	647.367	3.459	0.096
95% RFD/	FTP08	RFD95/MOL5 1	0.293	0.983	645.0	3.280	0.092
5% Mosstanol	FTP09	RFD95/MOL5 2	0.329	0.980	645.4	3.393	0.095

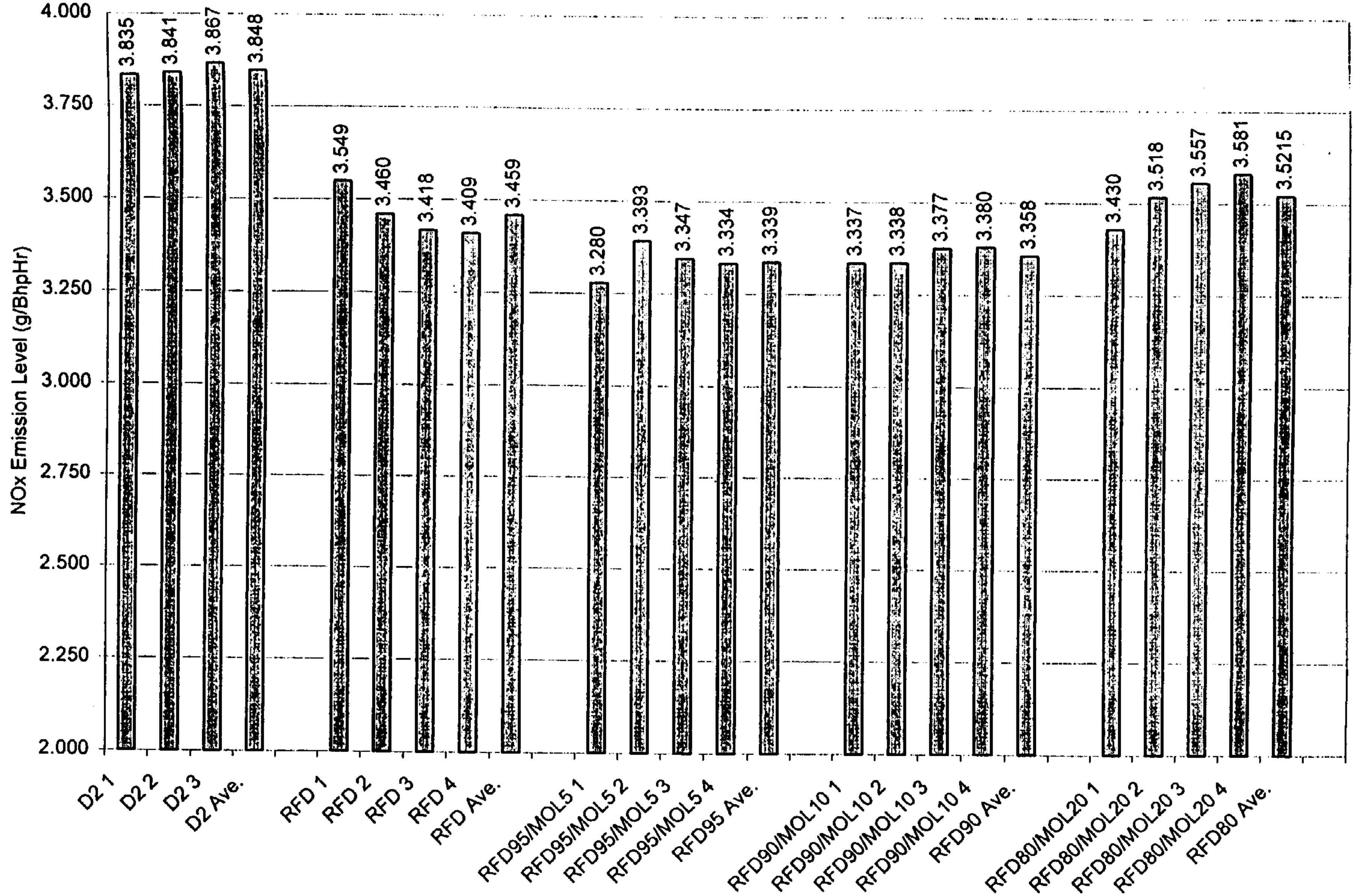
	FTP10	RFD95/MOL5 3	0.346	1.033	640.2	3.347	0.098
	FTP11	RFD95/MOL5 4	0.340	1.068	642.9	3.334	0.100
Average		RFD95 Ave.	0.327	1.016	643.383	3.339	0.096
90% RFD/	FTP12	RFD90/MOL10 1	0.512	1.137	640.5	3.337	0.105
10% Mosstanol	FTP13	RFD90/MOL10 2	0.530	1.123	644.5	3.338	0.107
	FTP14	RFD90/MOL10 3	0.548	1.195	645.8	3.377	0.104
	FTP15	RFD90/MOL10 4	0.538	1.188	638.2	3.380	0.104
Average		RFD90 Ave.	0.532	1.161	642.247	3.358	0.105
80% RFD/	FTP16	RFD80/MOL20 1	0.718	1.321	639.3	3.430	0.108
20% Mosstanol	FTP17	RFD80/MOL20 2	0.762	1.467	642.4	3.518	0.107
	FTP18	RFD80/MOL20 3	0.812	1.581	651.1	3.557	0.111
	FTP19	RFD80/MOL20 4	0.905	1.615	646.8	3.581	0.114
Average		RFD80 Ave.	0.7993	1.496	644.89	3.5215	0.11

	Percentage Reduction of each Emissions over D2 Value				
Positive values are emissions increases.	HC	CO	CO2	NOx	PM
RFD	**-7.8**	**-18.5**	**-3.4**	**-10.1**	**-14.8**
RFD+5%Mosstanol	**78.4**	**-6.9**	**-3.9**	**-13.2**	**-14.3**
RFD+10% Mosstanol	**190.2**	**6.4**	**-4.1**	**-12.7**	**-6.5**
RFD+20% Mosstanol	**336.0**	**37.1**	**-3.7**	**-8.5**	**-2.1**

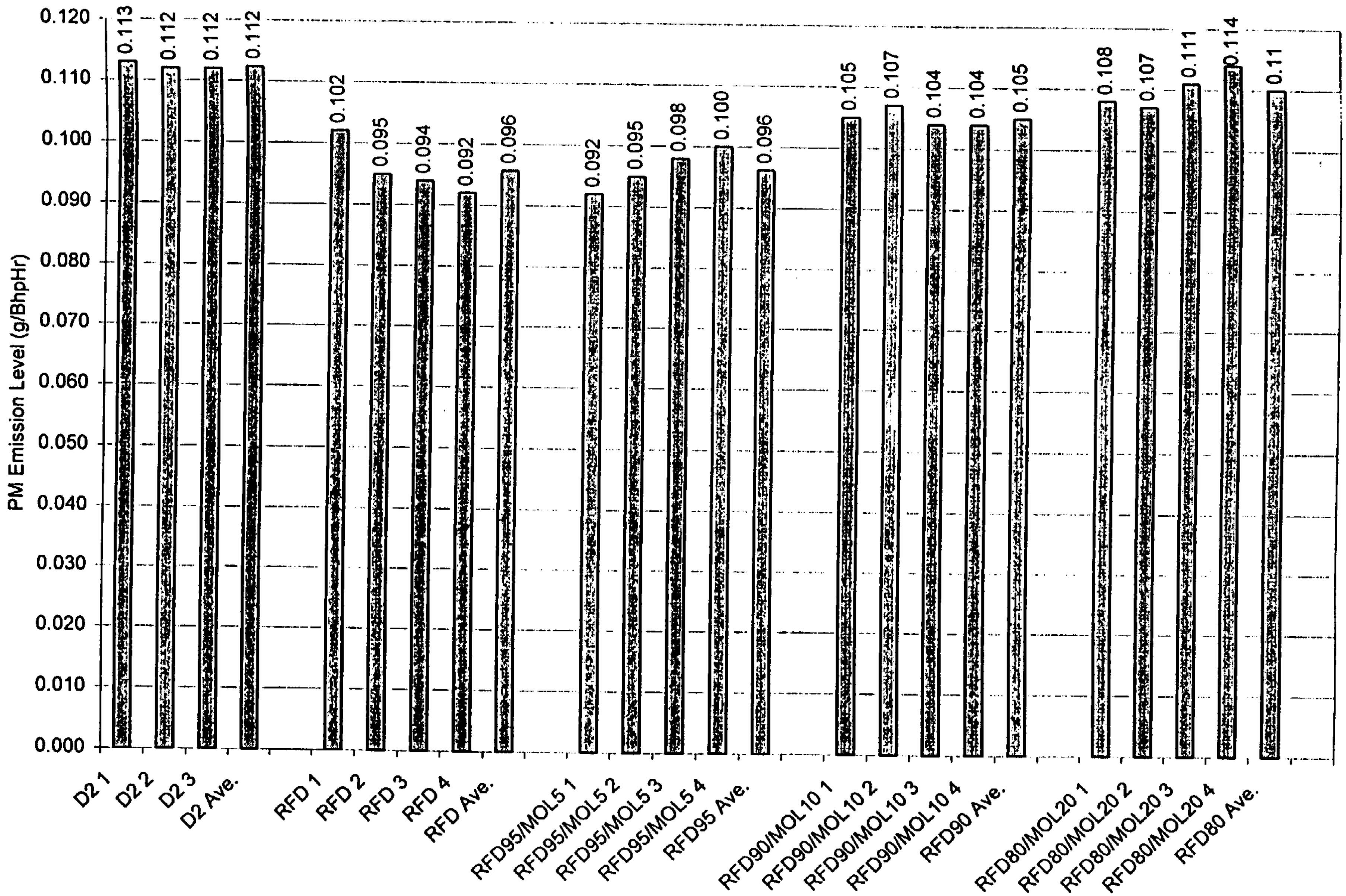


Navistar T444 Engine Testing

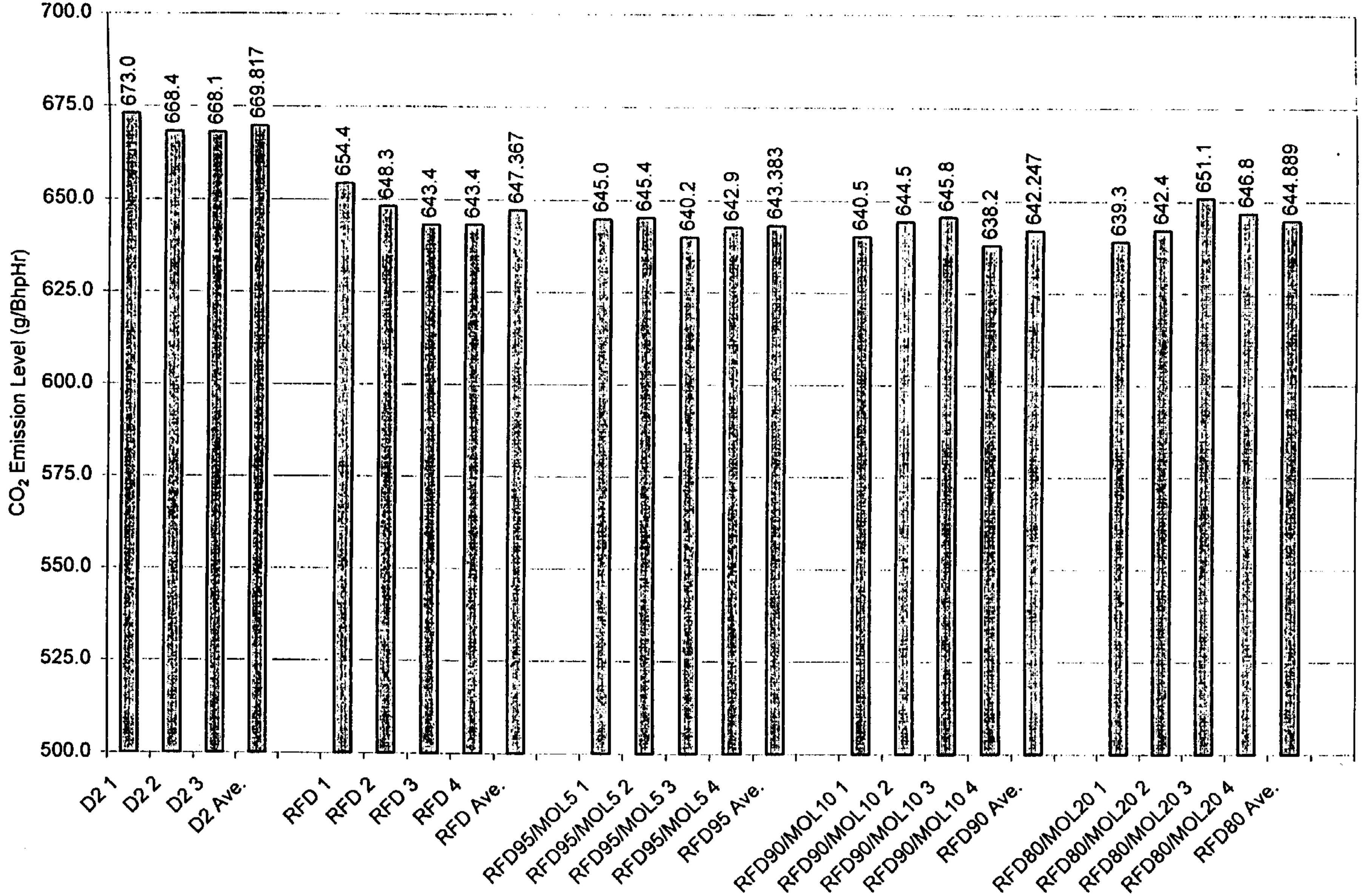

CO Emission Level (g/BhpHr)
2.000
1.500
1.000
0.500
0.000
1.099
1.093
1.082
1.091
0.943
0.863
0.913
0.840
0.890
0.983
0.980
1.033
1.068
1.016
1.137
1.123
1.195
1.188
1.161
1.321
1.467
1.581
1.615
1.496
D2 1
D2 2
D2 3
D2 Ave.
RFD 1
RFD 2
RFD 3
RFD 4
RFD Ave.
RFD95/MOL5 1
RFD95/MOL5 2
RFD95/MOL5 3
RFD95/MOL5 4
RFD95 Ave.
RFD90/MOL10 1
RFD90/MOL10 2
RFD90/MOL10 3
RFD90/MOL10 4
RFD90 Ave.
RFD80/MOL20 1
RFD80/MOL20 2
RFD80/MOL20 3
RFD80/MOL20 4
RFD80 Ave.



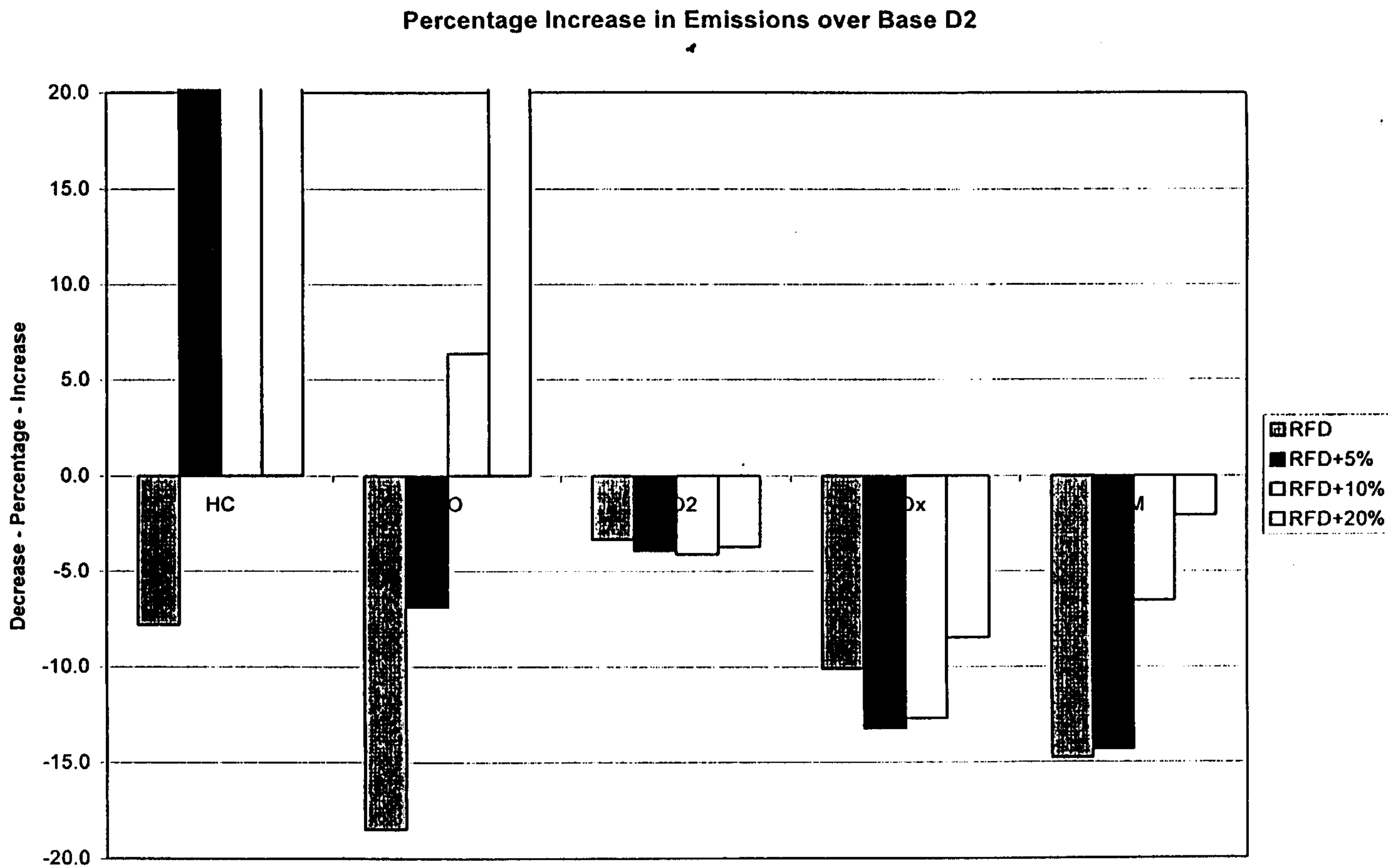
Navistar T444 Engine Testing

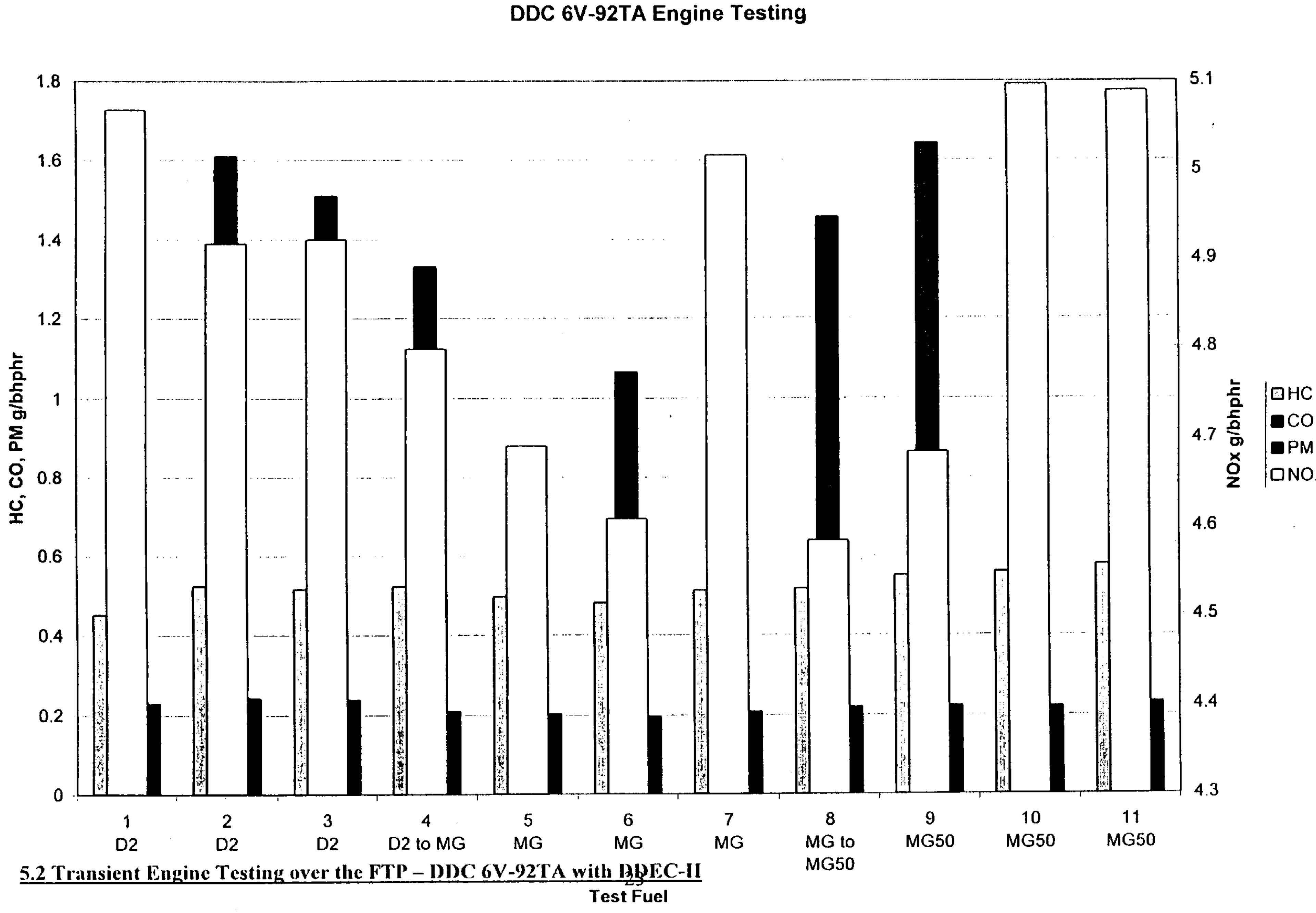


Navistar T444 Engine Testing



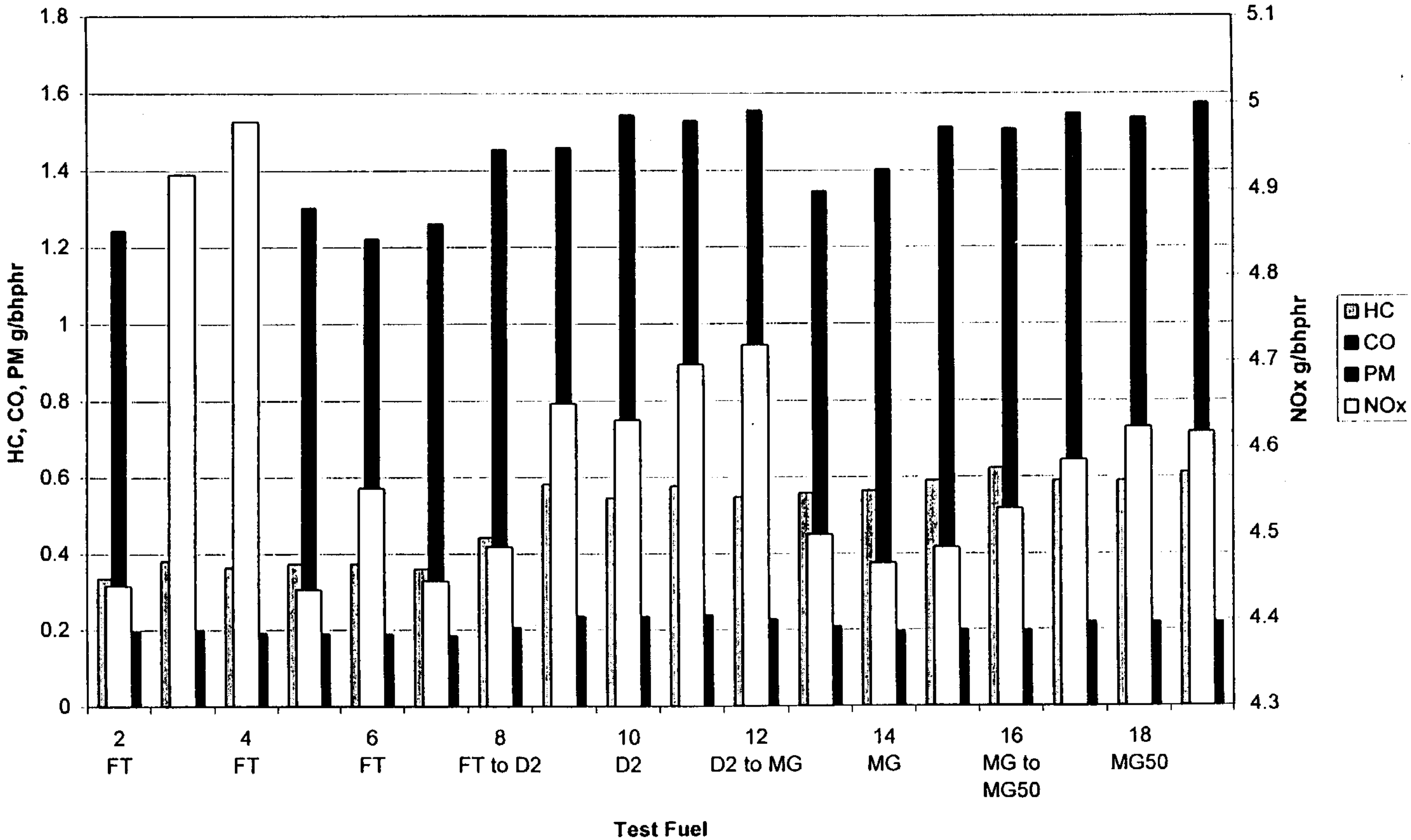
Navistar T444 Engine Testing

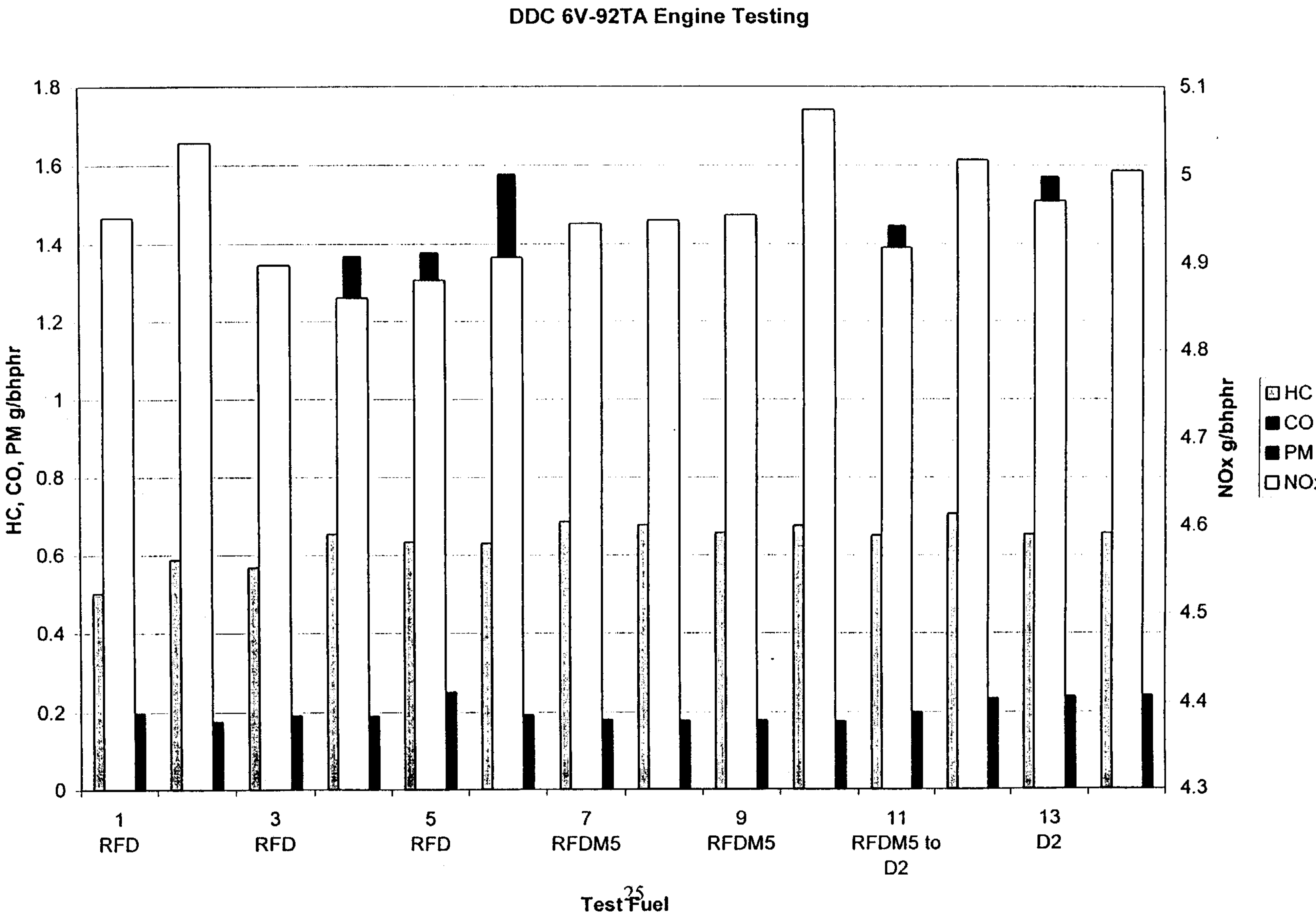

Percentage Increase in Emissions over Base D2
20.0
15.0
10.0
5.0
0.0
-5.0
-10.0
-15.0
-20.0
Decrease - Percentage - Increase
HC
RFD
RFD+5%
RFD+10%
RFD+20%



5.2 Transient Engine Testing over the FTP – DDC 6V-92TA with DDEC-II

DDC 6V-92TA Engine Testing




DDC 6V-92TA Engine Testing
HC, CO, PM g/bhphr
NOx g/bhphr
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
5.1
5
4.9
4.8
4.7
4.6
4.5
4.4
4.3
HC
CO
PM
NO:
1
RFD
3
RFD
5
RFD
7
RFDM5
9
RFDM5
11
RFDM5 to
D2
13
D2
Test Fuel

DDC 6V92 Engine Testing (all emissions in g/bhphr)

	D2	D2	D2	D2 to MG	MG	MG	MG	MG to MG50	MG50	MG50	MG50
	1	2	3	4	5	6	7	8	9	10	11
HC	0.451	0.523	0.515	0.522	0.496	0.481	0.512	0.516	0.551	0.56	0.578
CO	1.67	1.611	1.511	1.331	0.65	1.066	1.108	1.458	1.644	1.582	1.081
CO2	722.073	724.299	724.585	714.361	699.616	692.874	695.344	697.313	703.904	706.89	705.998
NOx	5.068	4.918	4.922	4.799	4.691	4.609	5.017	4.584	4.684	5.096	5.089
PM	0.23	0.243	0.24	0.21	0.204	0.197	0.209	0.219	0.224	0.222	0.232

	FT	FT	FT	FT	FT	FT	FT to D2	D2	D2	D2	D2 to MG	MG	MG	MG	MG to MG50	MG50	MG50	MG50
	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
HC	0.336	0.381	0.365	0.373	0.374	0.361	0.443	0.582	0.547	0.577	0.548	0.558	0.564	0.591	0.623	0.59	0.59	0.612
CO	1.244	1.188	1.261	1.305	1.222	1.262	1.455	1.461	1.544	1.53	1.556	1.348	1.404	1.513	1.508	1.548	1.537	1.576
CO2	679.884	680.077	682.849	674.95	679.459	671.694	691.868	711.709	717.251	716.883	709.58	695.638	697.933	705.016	689.746	702.558	707.776	707.569
NOx	4.44	4.918	4.979	4.435	4.554	4.446	4.486	4.652	4.633	4.697	4.72	4.5	4.467	4.485	4.53	4.586	4.624	4.618
PM	0.198	0.2	0.191	0.19	0.189	0.184	0.207	0.236	0.235	0.239	0.227	0.208	0.197	0.199	0.198	0.218	0.22	0.22

	RFD	RFD	RFD	RFD	RFD	RFD to RFDM 5	RFDM 5	RFDM 5	RFDM 5	RFDM 5	RFDM 5 to D2	D2	D2	D2
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
HC	0.502	0.588	0.569	0.654	0.633	0.631	0.686	0.677	0.658	0.676	0.651	0.706	0.653	0.657
CO	1.339	1.236	1.26	1.369	1.378	1.577	1.283	1.365	1.307	1.375	1.447	1.576	1.571	1.578
CO2	709.395	693.873	688.406	701.689	706.369	697.153	701.314	693.21	696.381	697.437	710.884	727.048	721.586	730.52
NOx	4.952	5.036	4.898	4.861	4.881	4.907	4.945	4.949	4.955	5.074	4.918	5.017	4.971	5.005
PM	0.2	0.177	0.193	0.192	0.253	0.195	0.182	0.18	0.181	0.178	0.201	0.236	0.241	0.244

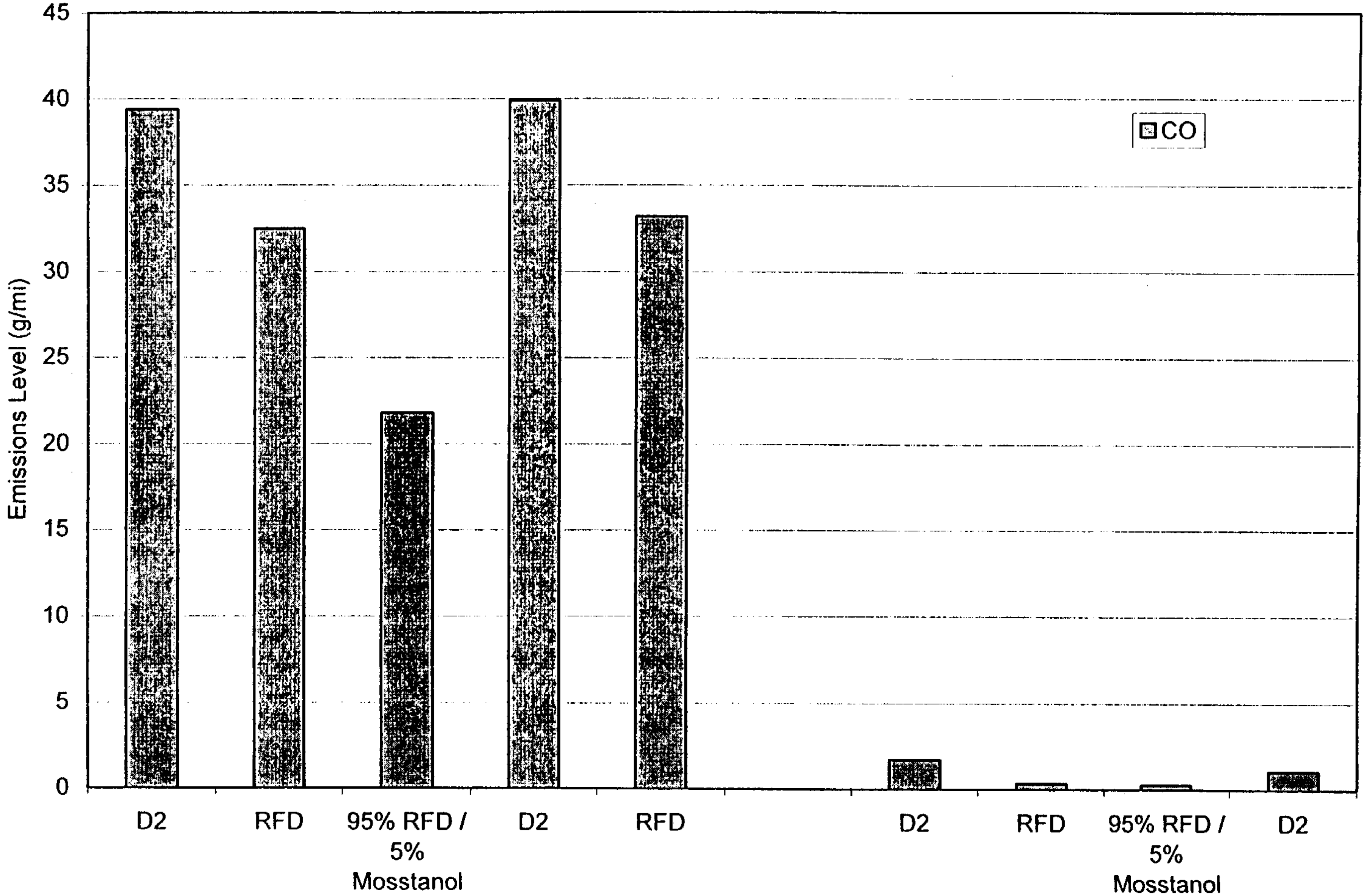
	HC	CO	CO2	NOx	PM
D2	0.50	1.60	723.65	4.97	0.24
MG	0.50	0.94	695.94	4.77	0.20
%Reduction MG over D2	0.00	-41.07	-3.83	-3.96	-14.45
D2	0.67	1.58	726.38	5.00	0.24
RFD	0.59	1.32	699.95	4.93	0.20
%Reduction RFD over D2	-12.32	-16.42	-3.64	-1.44	-15.53

DDC 6V92 Engine Dynamometer Testing – Percentage Emissions Reduction for COD and RFD Fuels over D2

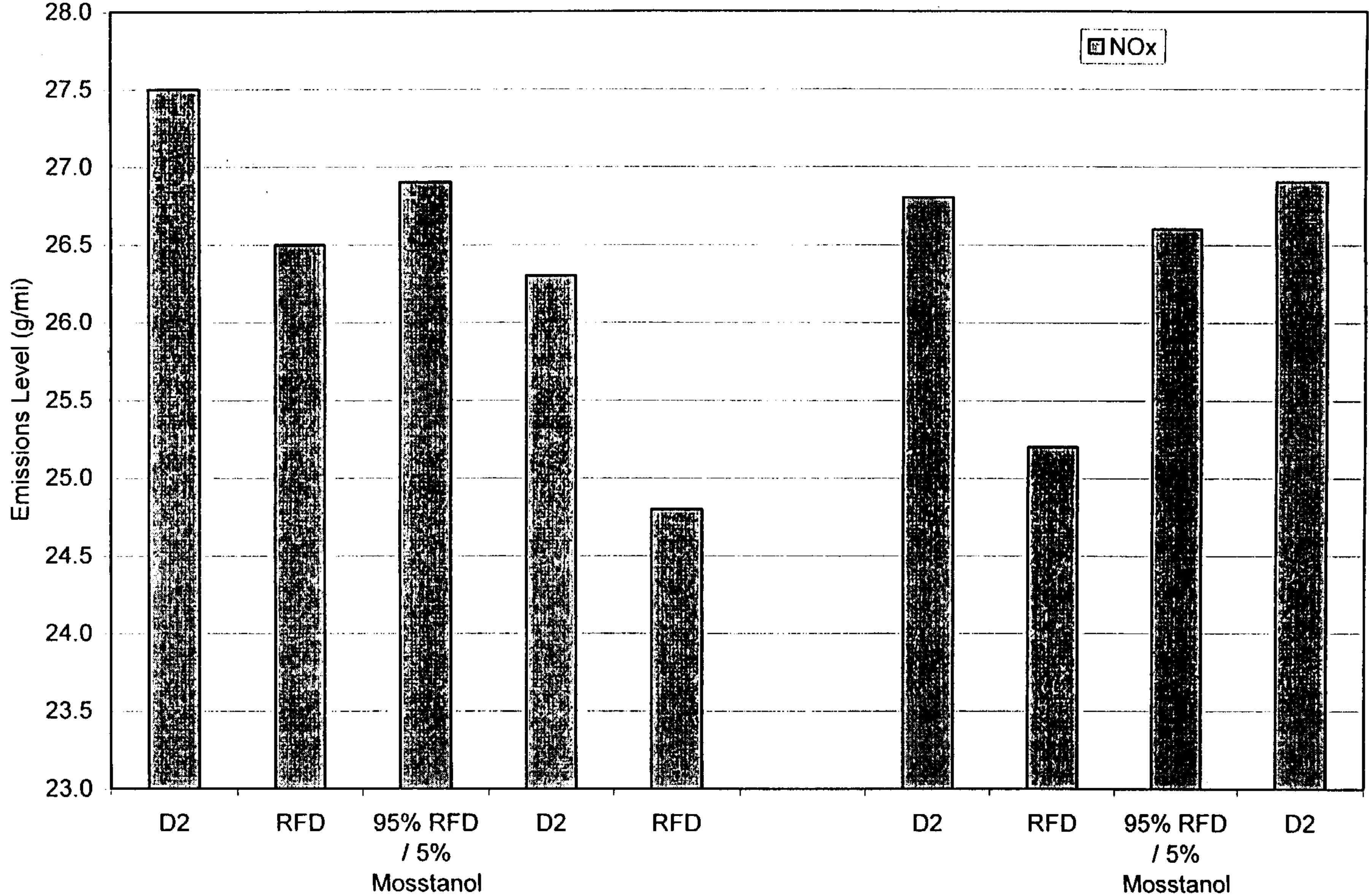
5.3 Transient Chassis Dynamometer Testing – Transit Bus Testing – Port Authority of Allegheny County

				Emissions Results (g/mile)					Fuel Economy	
	Sequence No.	Cycle	Fuel	CO	NOx	HC	PM	CO2	mile/ gal	BTU/ mile
Unmodified Bus#1	3093	CBD	D2	39.4	27.5	1.02	10	5059	1.99	65456
	3094	CBD	RFD	32.5	26.5	0.9	8.86	4908	1.86	66365
	3095	CBD	95% RFD / 5% Mosstanol	21.8	26.9	0.96	7.45	5034	1.82	67820
	3098	CBD	D2	39.9	26.3	1.33	8.93	4896	2.05	63398
	3099	CBD	RFD	33.2	24.8	1.07	8.56	4771	1.91	64549
	%Reduction RFD over D2			-17.15	-4.65	-16.17	-7.98	-2.77		
	%Reduction RFD95/5M over D2			-45.02	0.00	-18.30	-21.29	1.14		
Catalytic Converter Equipped Bus#2	3100	CBD	D2	1.72	26.8	0.43	1.69	4356	2.33	55705
	3112	CBD	RFD	0.38	25.2	0.4	1.27	4347	2.12	58157
	3113	CBD	95% RFD / 5% Mosstanol	0.27	26.6	0.42	0.97	4367	2.11	58424
	3114	CBD	D2	1.07	26.9	0.35	1.89	4458	2.28	56995
	%Reduction RFD over D2			-72.76	-6.15	2.56	-29.05	-1.36		
	%Reduction RFD95/5M over D2			-80.65	-0.93	7.69	-45.81	-0.91		

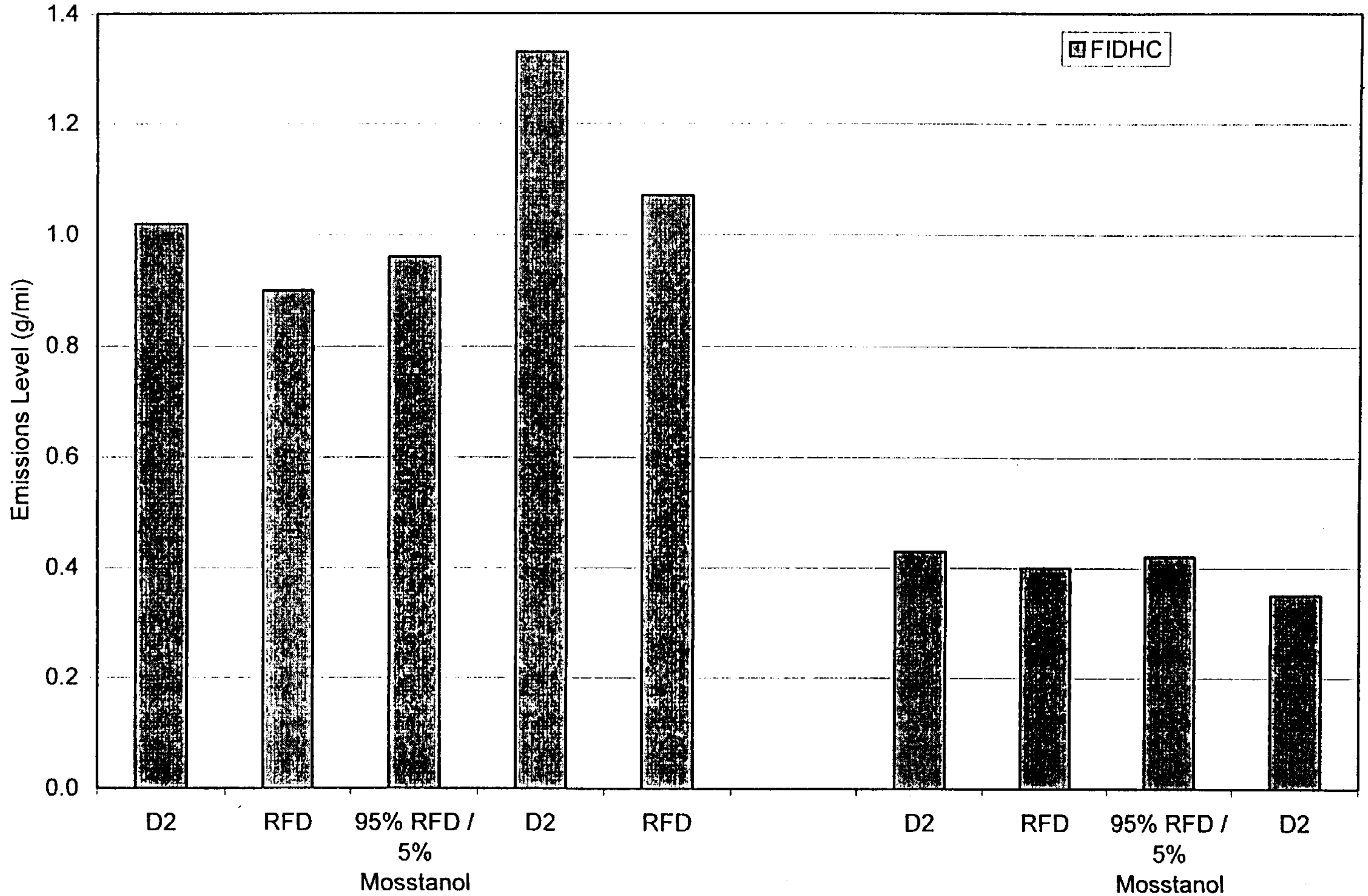
Table of Emissions Results for Unmodified Bus and Catalyst-Equipped Bus operating over the CBD – Chassis Dynamometer Results



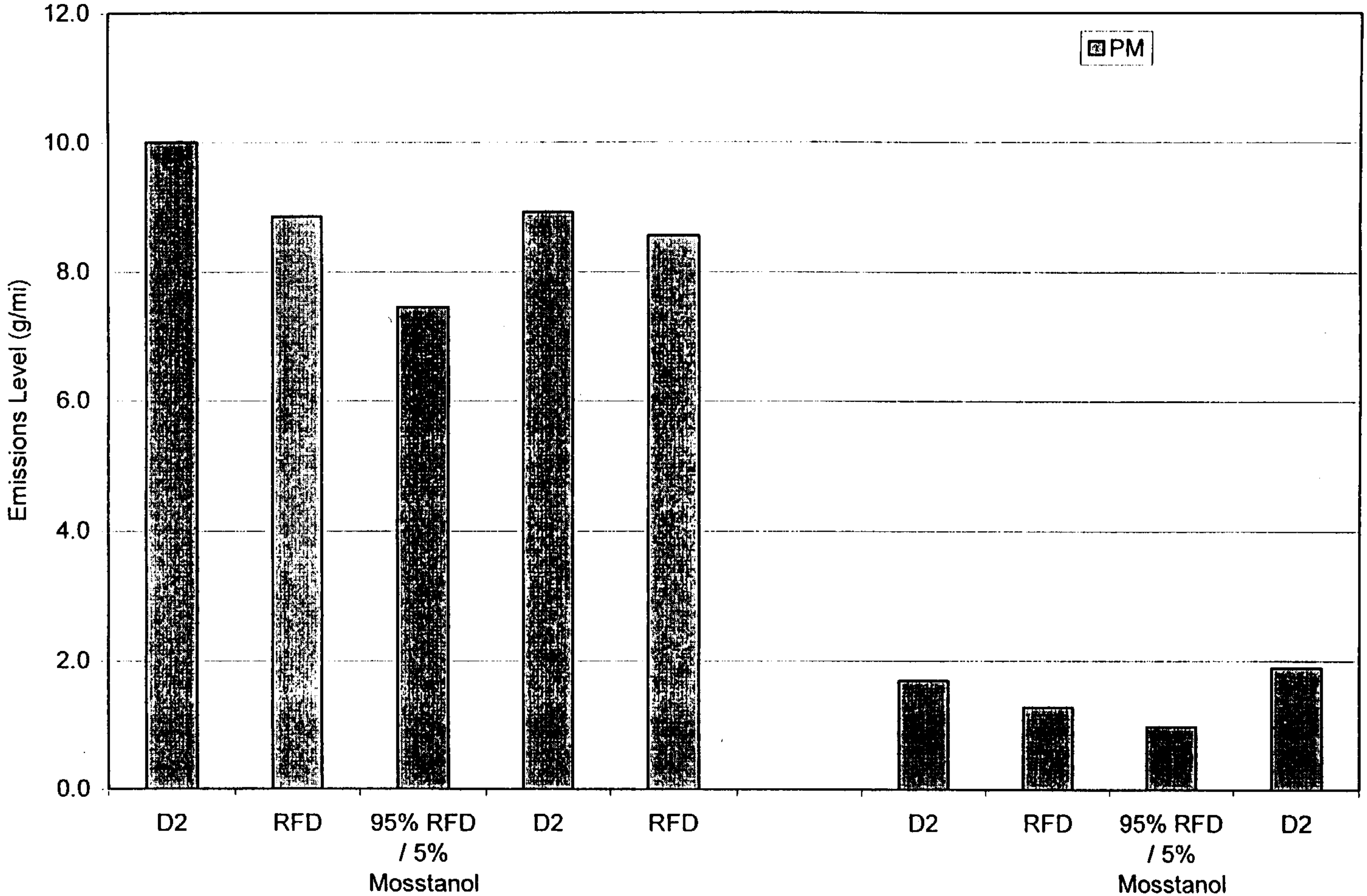
CO Emissions on the CBD for Unmodified Bus (left hand data set) and Catalyst-equipped Bus



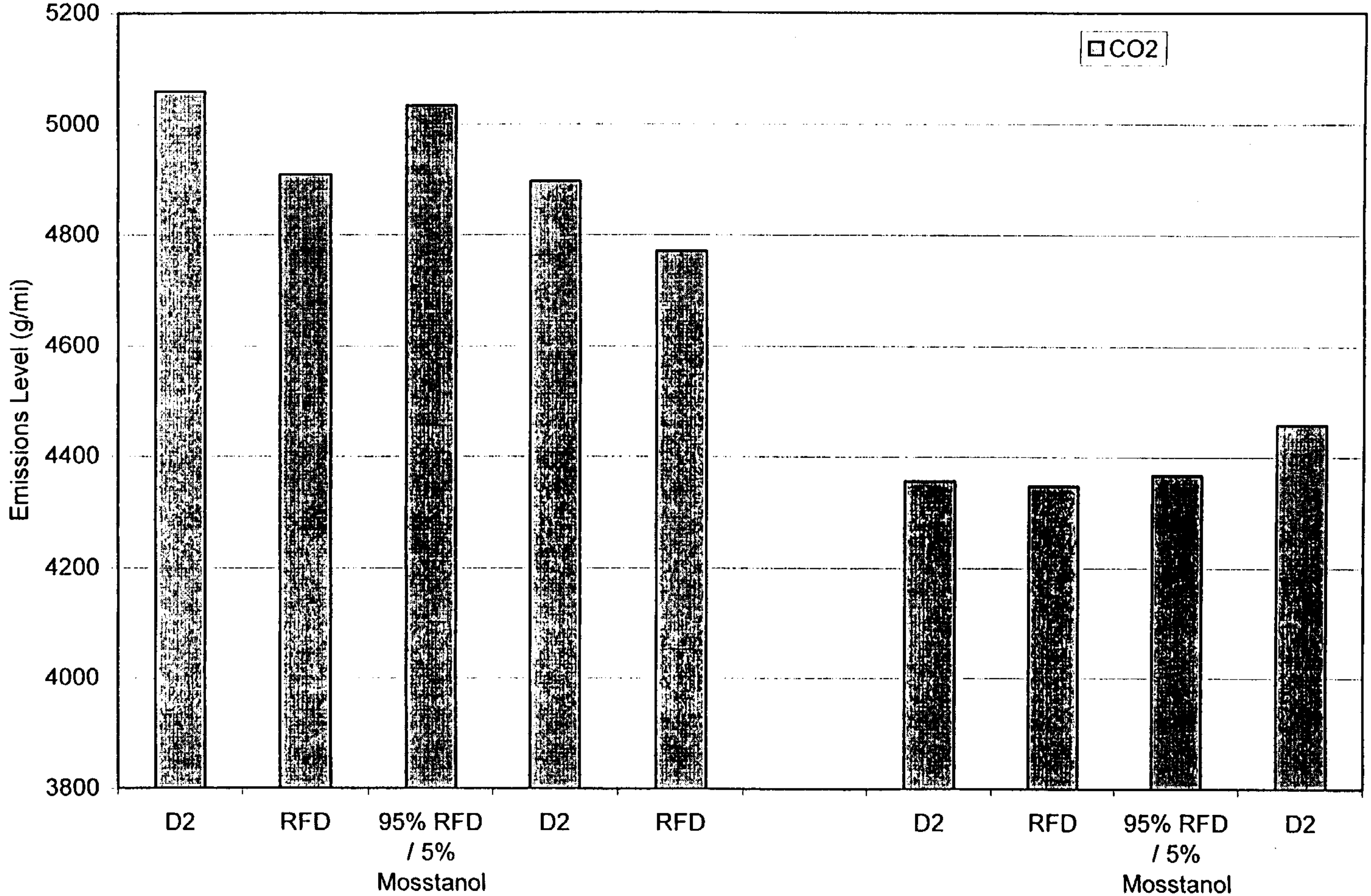
NOx Emissions on the CBD for Unmodified Bus (left hand data set) and Catalyst-equipped Bus



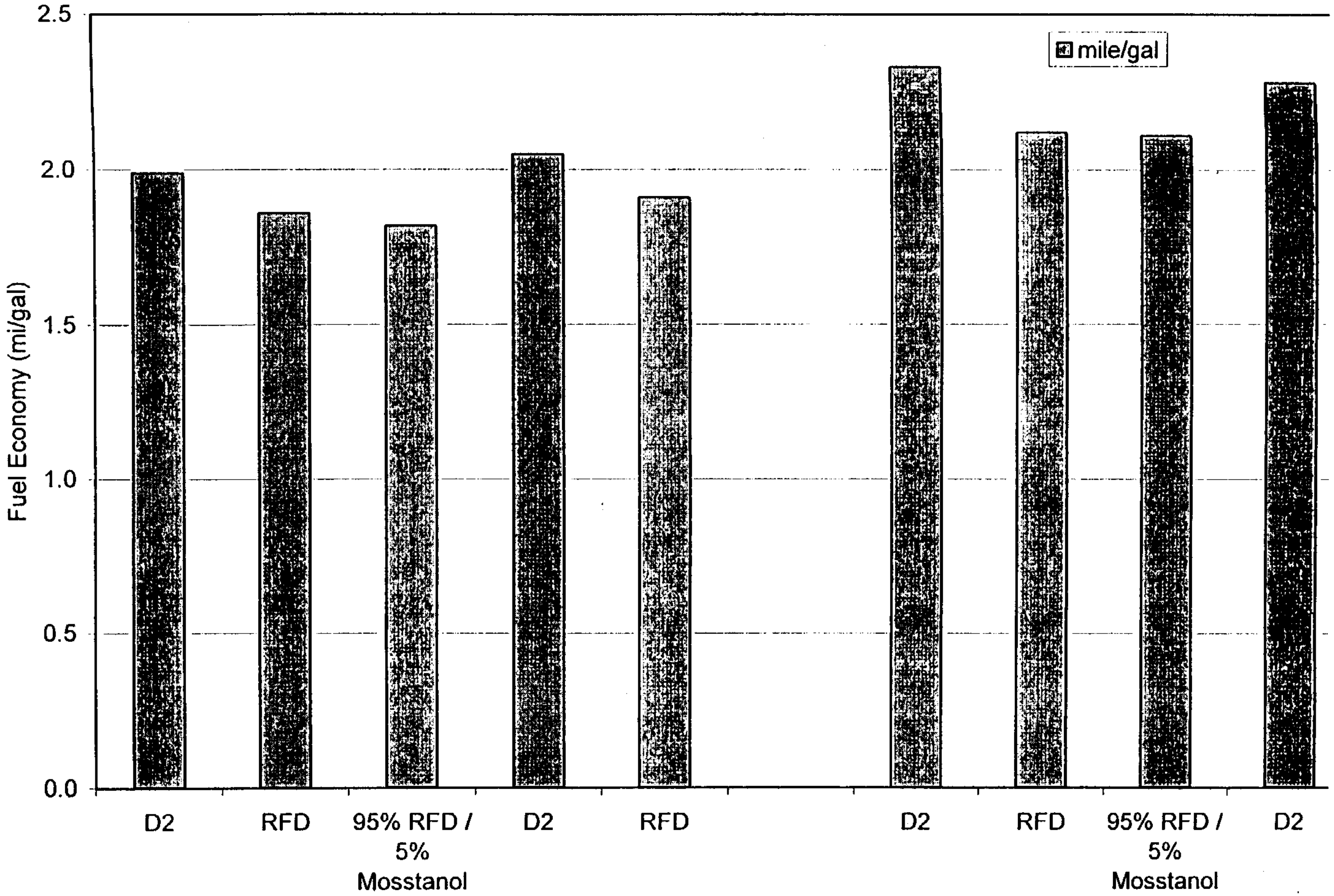
HC Emissions on the CBD for Unmodified Bus (left hand data set) and Catalyst-equipped Bus



PM Emissions on the CBD for Unmodified Bus (left hand data set) and Catalyst-equipped Bus



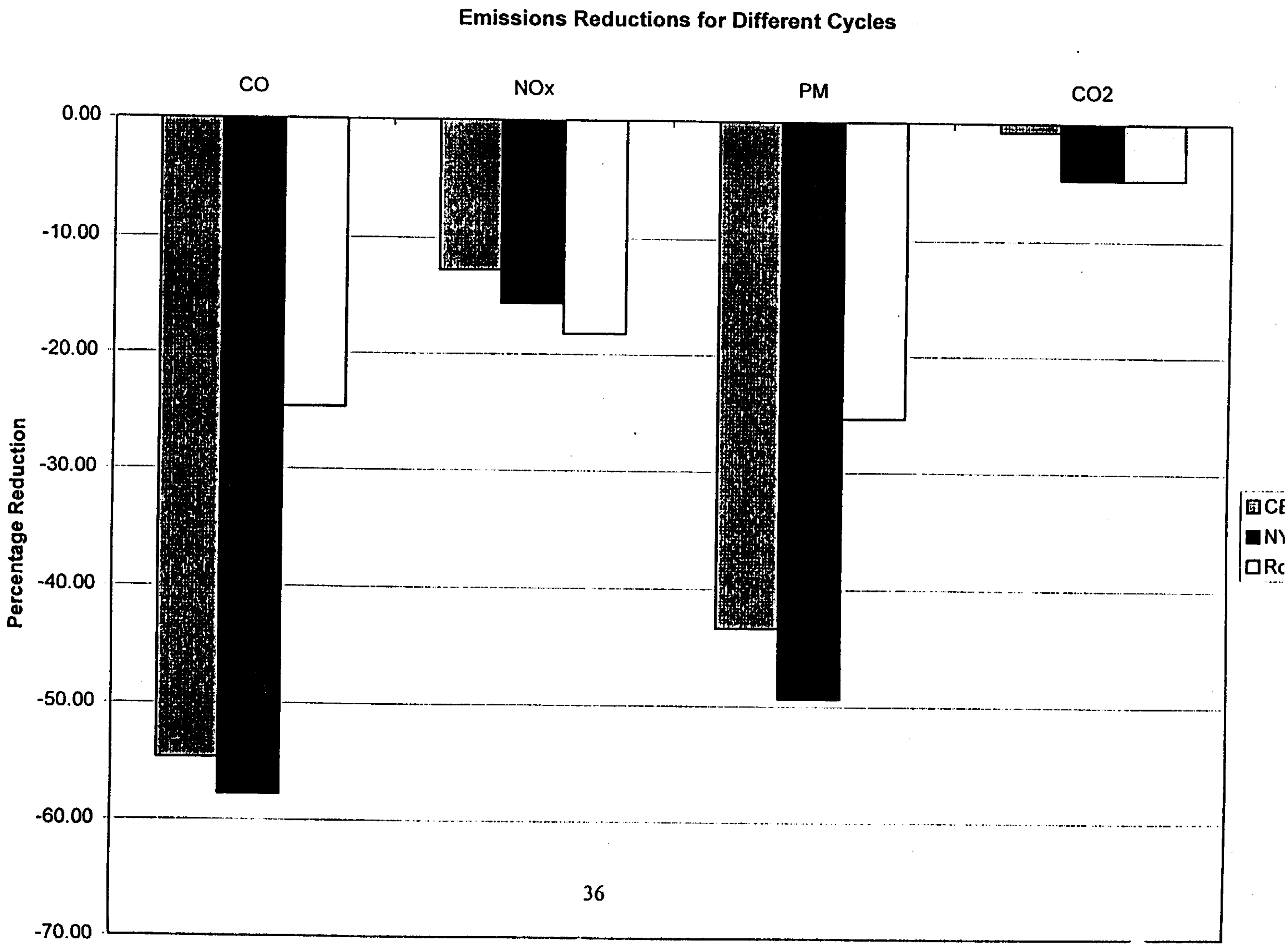
CO2 Emissions on the CBD for Unmodified Bus (left hand data set) and Catalyst-equipped Bus



Fuel Consumption over the CBD for Unmodified Bus and Catalyst-equipped Bus

5.4 Transient Chassis Dynamometer Testing – Transit Bus Testing – New York City Transit Authority

FUEL	CYCLE	Run Seq. No.	CO	NOx	FIDHC	PM	CO2	mile/gal	BTU/mile	Miles
D1	CBD	3194 Average	2.27	36.9	0.04	0.150	2837	3.39	37120	2.02
D1	CBD	3196 Average	1.91	36.5	0.06		2900	3.32	37938	2.02
MG	CBD	3191 Average	1.03	32.2	0.05	0.085	2816	3.28	37684	2.01
		% Reduction MG over D2	-54.63	-12.74		-43.33	-0.74			
D1	NY Bus	3197 Average	15.50	85.7	0.12	0.730	7639	1.26	100162	0.56
MG	NY Bus	3192 Average	6.55	72.3	0.15	0.370	7272	1.27	97399	0.56
		%Reduction MG over D2	-57.74	-15.64		-49.32	-4.80			
D1	Route 22	3198 Average	2.60	32.9	0.10	0.130	2506	3.84	32809	2.02
MG	Route 22	3193 Average	1.96	26.9	0.15	0.097	2386	3.87	31952	2.01
		%Reduction MG over D2	-24.62	-18.24		-25.38	-4.79			



Emissions Reductions for Different Cycles
CO
NOx
PM
CO2
0.00
-10.00
-20.00
-30.00
-40.00
-50.00
-60.00
-70.00
Percentage Reduction
CE
NY
Rc

6. Conclusions

It has been shown that there are significant emissions reduction benefits to be obtained from the use of zero sulphur, low aromatic, relatively high cetane number distillate fuels with or without the use of oxygenates.

The following specific conclusions can be drawn from the testing performed, namely

- For the Navistar HD four stroke engine testing, reductions of 10-13% in NOx and up to 15% in PM were obtained using RFD and 5% Mosstanol in RFD, with no deleterious effects in the other emissions levels (HC and CO emissions remain well below regulated levels). It should be borne in mind that the engine used was unmodified, and that injection timing modifications could probably be used to obtain significantly lower PM emissions for the same overall NOx emissions levels, or vice versa. This testing shows that there is a significant potential for the use of a mildly oxygenated, zero sulphur, moderate cetane number distillate fuel in modern four stroke HD truck engines.

- For the DDC 6V-92 engine testing, similar simultaneous reductions in NOx (1-2%) and PM (up to 15%) were achieved, showing the benefit of either neat RFD or the RFD95/M5 blend in reducing the emissions from an unmodified 2-stroke engine used in transit bus application. Similar PM reductions were seen using the COD fuel, leading to the conclusion that the zero S fuel specification leads to similar reductions in PM regardless of engine technology, as this trend was noted for both 2 and 4 stroke cycle engines.

- For the DDC 6V-92 bus testing, both the RFD and the RFD95/M5 blend demonstrate significant emissions reductions benefits for NOx, PM and CO in both an unmodified bus and in a retrofitted bus using an oxidation catalyst. The fuel effect carries over from the uncatalysed bus (8-15% PM reduction) to the catalysed bus (30-45% PM reduction), and is independent of the absolute level of emissions of the exhaust constituent. This implies that the RFD or oxygenated RFD will be equally beneficial in buses with or without aftertreatment, although the zero S specification of the fuel will be especially attractive for use in vehicles with sulphur-sensitive aftertreatment devices. In fact these fuels might have a larger impact on catalysed engine emissions as seen by these results.

- For the DDC Series 50 bus testing, using the COD fuel NOx was reduced by 12-18% across the three different transient cycles employed, while PM was reduced an even greater 25-50%. This particular bus represents currently prevailing emissions certification standards, and it is encouraging to note that the emissions reduction benefits of Mossgas fuel holds, even for relatively low emitting four stroke cycle bus engines.

- In summary, it has been found that Mossgas fuels offer simultaneous reduction of NOx and PM in both 2 and 4 stroke cycle heavy duty direct injection turbocharged diesel engines, in real-world vehicle testing, in engines ranging in vintage from 1991 to 1999, in catalysed and non-catalysed applications, and across a range of vehicle driving cycles.

7. Recommendations

The following recommendations are offered as a result of the work performed in this project:

- Injection Timing Optimization: A study should be made of the maximum potential benefits of optimization of injection timing on reducing the emissions from FT-fueled HD diesel engines. For example, injection timing can be advanced across the board with FT fuels to give the same NOx emissions as D2 with substantially reduced PM. Alternatively if the goal is to minimize NOx emissions (noting the poor relative efficiency of lean NOx conversion techniques), a relatively higher level of PM emissions can be tolerated with these fuels as particulate traps or filters can readily be used to reduce the exhaust PM levels.

- Exhaust Gas Recirculation: The potential synergistic effects of these zero S fuels on facilitating the use of relatively large amounts of EGR in HD diesel engines should be investigated. Due to the reduced PM emissions with these fuels, greater amounts of EGR can be returned to the engine without the fear of excessive wear due to high soot production levels.

- Exhaust Aftertreatment - NOx: The zero S specification of these fuels makes them prime candidates for sulphur-sensitive aftertreatment devices such as lean NOx catalysts, or de-NOx systems. Demonstration of these fuels with these sophisticated aftertreatment devices should be considered.

- Exhaust Aftertreatment – PM: Demonstration of these fuels with PM filters or traps (such as the Johnson Matthey CRT aftertreatment device) should be considered.

- Water Injection or Water Emulsion Fuels: The use of these fuels in a test engine employing water injection should be considered, as should the compatibility of these fuels in stabilized water emulsions.

- Oxygenates: The use of alternative oxygenates in Mossgas diesel fuels should be considered, including the range of ethers now being considered elsewhere (such as DMM, DME etc.). Moreover, the use of cetane enhancers should also be considered.

- Vehicle Demonstrations: The use of Mossgas fuels in future line haul and transit bus demonstration projects should be considered, including in both light and heavy duty hybrid electric vehicle applications.

- Future Applications: It is clear that an excellent fuel for fuel cell applications (employing on-board reformation) could be produced from natural gas, namely a zero sulphur, highly saturated naptha, gasoline or distillate. While the diesel engine has many years of life left in it, long term consideration should be given to future fuels such as these and other alternative future liquid fuel applications.

DEFINITIONS, ACRONYMS, ABBREVIATIONS

CBD – Central Business District (driving cycle)
CO – Carbon Monoxide
COD – Conversion of Olefins to Diesel
DDC – Detroit Diesel Corporation
DOE – U.S. Department of Energy
EPA – Environmental Protection Agency
EPACT – Energy Policy Act of 1992
FBP – Final Boiling Point
FIA – Fluorescent Indicator Adsorption
F-T diesel – Fischer-Tropsch diesel
FTP – Federal Test Procedure
GTL – Gas-to-liquids
HC – Hydrocarbons
HFRR – High Frequency Reciprocating Rig
IBP – Initial Boiling Point
MG – Mossgas synthetic diesel
NO_x – Oxides of Nitrogen
NREL – National Renewable Energy Laboratory
PM – Particulate Matter
ppm – parts per million
THC – Total Hydrocarbons
WVU – West Virginia University

Test Sequence Number: 3191
WVU Test Reference Number: NYCTA-5190-MG

Fleet Owner Full Name	New York City Transit Authority
Fleet Address	25 Jamaica Ave.
Fleet Address (City, State, Zip)	Brooklyn NY 11207
Vehicle Type	Bus
Vehicle ID Number (VIN)	4RKMNTGA7XR833764
Vehicle Manufacturer	TMC
Vehicle Model Year	1999
Gross Vehicle Weight (GVW) (lb.)	39500
Vehicle Total Curb Weight (lb.)	30700
Vehicle Tested Weight (lb.)	32250
Odometer Reading (mile)	245
Transmission Type	Automatic
Transmission Configuration	3-Speed
Number of Axles	2
Engine Type	Detroit Diesel Corp. Series 50
Engine ID Number	04R0026444
Engine Displacement (Liter)	8.5
Number of Cylinders	4
Engine Rated Power (hp)	275
Primary Fuel	FT-MGCOD
Test Cycle	CBD
Test Date	4/16/99
Engineer	Kopasko, Jim
Driver	England, Jason

Emissions Results (g/mile) / Fuel Economy

Run Seq. No.	CO	NO_x	FIDHC	PM	CO_2	mile/gal	BTU/mile	Miles
3191-1	1.02	32.7	0.051	0.073	2855	3.23	38205	2.01
3191-2	0.92	32.5	0.060	0.090	2820	3.27	37729	2.02
3191-3	1.14	31.4	0.031	0.093	2774	3.33	37118	2.01
3191 Average	1.03	32.2	0.047	0.085	2816	3.28	37684	2.01
Std. Dev.	0.11	0.7	0.015	0.011	41	0.05	545	0.01
CV%	10.8	2.2	31.2	13.1	1.5	1.4	1.4	0.4

Test Purpose:
M.J. Bradley Transit Bus Emissions Testing

Special Procedures:
Testing with FT-MGCOD (Moss-Gas) Fuel, bypassing the vehicle's fuel tank and running from a 55 gallon barrel. Particulate filters were saved for later speciation by M. J. Bradley & Associates

Observations:
Using LCO continuous to calculate the CO for the report. Speed sensor: We read 600 rpm at idle, which is 700 rpm. The FID HC analyzer was calibrated on the lowest possible range, 10-ppm propane (30 ppm HC). Essentially, HC levels were at or near the background measurements.

Test Sequence Number: 3192

WVU Test Reference Number: NYCTA-5190-MG-NYBUS

Fleet Owner Full Name	New York City Transit Authority
Fleet Address	25 Jamaica Ave.
Fleet Address (City, State, Zip)	Brooklyn NY 11207
Vehicle Type	Bus
Vehicle ID Number (VIN)	4RKMNTGA7XR833764
Vehicle Manufacturer	TMC
Vehicle Model Year	1999
Gross Vehicle Weight (GVW) (lb.)	39500
Vehicle Total Curb Weight (lb.)	30700
Vehicle Tested Weight (lb.)	32250
Odometer Reading (mile)	245
Transmission Type	Automatic
Transmission Configuration	3-Speed
Number of Axles	2
Engine Type	Detroit Diesel Corp. Series 50
Engine ID Number	04R0026444
Engine Displacement (Liter)	8.5
Number of Cylinders	4
Engine Rated Power (hp)	275
Primary Fuel	FT-MGCOD
Test Cycle	NYBus
Test Date	4/16/99
Engineer	Kopasko, Jim
Driver	England, Jason

Emissions Results (g/mile) / Fuel Economy

Run Seq. No.	CO	NO_x	FIDHC	PM	CO_2	mile/gal	BTU/mile	Miles
3192-1	6.62	71.7	0.17	0.35	7141	1.29	95646	0.56
3192-3	6.78	74.1	0.14	0.39	7502	1.23	100477	0.55
3192-4	6.26	71.1	0.13	0.36	7174	1.29	96075	0.56
3192 Average	6.55	72.3	0.15	0.37	7272	1.27	97399	0.56
Std. Dev.	0.26	1.6	0.02	0.02	200	0.03	2674	0.00
CV%	4.0	2.2	13.1	5.2	2.7	2.7	2.7	0.9

Test Purpose:
M.J. Bradley Transit Bus Emissions Testing

Special Procedures:
Testing with FT-MGCOD (Moss-Gas) Fuel, bypassing the vehicle's fuel tank and running from a 55 gallon barrel. Particulate filters were saved for later speciation by M. J. Bradley & Associates

Observations:
Using LCO continuous to calculate the CO for the report. Speed sensor: We read 600 rpm at idle, which is 700 rpm. The FID HC analyzer was calibrated on the lowest possible range, 10-ppm propane (30 ppm HC). Essentially, HC levels were at or near the background measurements. During run #2, a CNG vehicle was started up inside the building, and one of the bay doors was opened while another CNG vehicle was driven into the building. This test was marked invalid and removed from the average.

Test Sequence Number: 3193
WVU Test Reference Number: NYCTA-5190-MG-route22

Fleet Owner Full Name	New York City Transit Authority
Fleet Address	25 Jamaica Ave.
Fleet Address (City, State, Zip)	Brooklyn NY 11207
Vehicle Type	Bus
Vehicle ID Number (VIN)	4RKMNTGA7XR833764
Vehicle Manufacturer	TMC
Vehicle Model Year	1999
Gross Vehicle Weight (GVW) (lb.)	39500
Vehicle Total Curb Weight (lb.)	30700
Vehicle Tested Weight (lb.)	32250
Odometer Reading (mile)	245
Transmission Type	Automatic
Transmission Configuration	3-Speed
Number of Axles	2
Engine Type	Detroit Diesel Corp. Series 50
Engine ID Number	04R0026444
Engine Displacement (Liter)	8.5
Number of Cylinders	4
Engine Rated Power (hp)	275
Primary Fuel	FT-MGCOD
Test Cycle	Route-22
Test Date	4/16/99
Engineer	Kopasko, Jim
Driver	England, Jason

Emissions Results (g/mile) / Fuel Economy

Run Seq. No.	CO	NO_x	FIDHC	PM	CO_2	mile/gal	BTU/mile	Miles
3193-1	1.96	26.9	0.15	0.097	2386	3.87	31952	2.01
3193 Average	1.96	26.9	0.15	0.097	2386	3.87	31952	2.01
Std. Dev.	0.00	0.0	0.00	0.000	0	0.00	0	0.00
CV%	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Test Purpose:
M.J. Bradley Transit Bus Emissions Testing and cycle development.

Special Procedures:
Testing with FT-MGCOD (Moss-Gas) Fuel, bypassing the vehicle's fuel tank and running from a 55 gallon barrel. Particulate filters were saved for later speciation by M. J. Bradley & Associates

Observations:
Using LCO continuous to calculate the CO for the report. Speed sensor: We read 600 rpm at idle, which is 700 rpm. The FID HC analyzer was calibrated on the lowest possible range, 10-ppm propane (30 ppm HC). Essentially, HC levels were at or near the background measurements.

Test Sequence Number: 3194
WVU Test Reference Number: NYCTA-5190-D1

Fleet Owner Full Name	New York City Transit Authority
Fleet Address	25 Jamaica Ave.
Fleet Address (City, State, Zip)	Brooklyn NY 11207
Vehicle Type	Bus
Vehicle ID Number (VIN)	4RKMNTGA7XR833764
Vehicle Manufacturer	TMC
Vehicle Model Year	1999
Gross Vehicle Weight (GVW) (lb.)	39500
Vehicle Total Curb Weight (lb.)	30700
Vehicle Tested Weight (lb.)	32250
Odometer Reading (mile)	245
Transmission Type	Automatic
Transmission Configuration	3-Speed
Number of Axles	2
Engine Type	Detroit Diesel Corp. Series 50
Engine ID Number	04R0026444
Engine Displacement (Liter)	8.5
Number of Cylinders	4
Engine Rated Power (hp)	275
Primary Fuel	D1
Test Cycle	CBD
Test Date	4/16/99
Engineer	Kopasko, Jim
Driver	England, Jason

Emissions Results (g/mile) / Fuel Economy

Run Seq. No.	CO	NO_x	FIDHC	PM	CO_2	mile/gal	BTU/mile	Miles
3194-1	2.13	37.4	0.040	0.14	2867	3.36	37512	2.02
3194-2	2.20	36.7	0.036	0.17	2814	3.42	36829	2.02
3194-3	2.47	36.7	0.037	0.15	2828	3.40	37018	2.02
3194 Average	2.27	36.9	0.038	0.15	2837	3.39	37120	2.02
Std. Dev.	0.18	0.4	0.002	0.01	27	0.03	353	0.00
CV%	8.0	1.1	5.9	8.4	1.0	0.9	1.0	0.1

Test Purpose:
M.J. Bradley Transit Bus Emissions Testing

Special Procedures:
Particulate filters were saved for later speciation by M. J. Bradley & Associates.

Observations:
Using LCO continuous to calculate the CO for the report. Speed sensor: We read 600 rpm at idle, which is 700 rpm. The FID HC analyzer was calibrated on the lowest possible range, 10-ppm propane (30 ppm HC). Essentially, HC levels were at or near the background measurements. The test fuel is listed ad Diesel # 1, but we are currently waiting on a fuel analysis to determine whether it was Diesel # 1 or #2. After run #1, recalibrated HC because it was drifting. The recalibration or drift appeared to have no affect on the measurements.

Test Sequence Number: 3196
WVU Test Reference Number: NYCTA-5190-D1

Fleet Owner Full Name	New York City Transit Authority
Fleet Address	25 Jamaica Ave.
Fleet Address (City, State, Zip)	Brooklyn NY 11207
Vehicle Type	Bus
Vehicle ID Number (VIN)	4RKMNTGA7XR833764
Vehicle Manufacturer	TMC
Vehicle Model Year	1999
Gross Vehicle Weight (GVW) (lb.)	39500
Vehicle Total Curb Weight (lb.)	30700
Vehicle Tested Weight (lb.)	32250
Odometer Reading (mile)	245
Transmission Type	Automatic
Transmission Configuration	3-Speed
Number of Axles	2
Engine Type	Detroit Diesel Corp. Series 50
Engine ID Number	04R0026444
Engine Displacement (Liter)	8.5
Number of Cylinders	4
Engine Rated Power (hp)	275
Primary Fuel	D1
Test Cycle	CBD
Test Date	4/17/99
Engineer	Kopasko, Jim
Driver	England, Jason

Emissions Results (g/mile) / Fuel Economy

Run Seq. No.	CO	NO_x	FIDHC	PM	CO_2	mile/gal	BTU/mile	Miles
3196-1	1.91	36.5	0.056	–	2900	3.32	37938	2.02
3196 Average	1.91	36.5	0.056	–	2900	3.32	37938	2.02
Std. Dev.	0.00	0.0	0.000	0.000	0	0.00	0	0.00
CV%	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Test Purpose:
M.J. Bradley Transit Bus Emissions Testing

Special Procedures:

Observations:
Using LCO continuous to calculate the CO for the report. Speed sensor: We read 600 rpm at idle, which is 700 rpm. The FID HC analyzer was calibrated on the lowest possible range, 10-ppm propane (30 ppm HC). Essentially, HC levels were at or near the background measurements. The test fuel is listed ad Diesel # 1, but we are currently waiting on a fuel analysis to determine whether it was Diesel # 1 or #2. This was a practice test. No particulate filter taken. Just to see what it looked like compared to the end of the day yesterday. This was the first run of the day, used to maintain continuity from the previous day's testing.

Test Sequence Number: 3197
WVU Test Reference Number: NYCTA-5190-D1-NYBUS

Fleet Owner Full Name	New York City Transit Authority
Fleet Address	25 Jamaica Ave.
Fleet Address (City, State, Zip)	Brooklyn NY 11207
Vehicle Type	Bus
Vehicle ID Number (VIN)	4RKMNTGA7XR833764
Vehicle Manufacturer	TMC
Vehicle Model Year	1999
Gross Vehicle Weight (GVW) (lb.)	39500
Vehicle Total Curb Weight (lb.)	30700
Vehicle Tested Weight (lb.)	32250
Odometer Reading (mile)	245
Transmission Type	Automatic
Transmission Configuration	3-Speed
Number of Axles	2
Engine Type	Detroit Diesel Corp. Series 50
Engine ID Number	04R0026444
Engine Displacement (Liter)	8.5
Number of Cylinders	4
Engine Rated Power (hp)	275
Primary Fuel	D1
Test Cycle	NYBus
Test Date	4/17/99
Engineer	Kopasko, Jim
Driver	England, Jason

Emissions Results (g/mile) **Fuel Economy**

Run Seq. No.	CO	NO_x	FIDHC	PM	CO_2	mile/gal	BTU/mile	Miles
3197-1	15.6	86.2	0.11	0.80	7801	1.23	102278	0.56
3197-2	14.8	85.0	0.14	0.71	7729	1.24	101328	0.56
3197-3	16.0	85.8	0.12	0.69	7387	1.30	96879	0.57
3197 Average	15.5	85.7	0.12	0.73	7639	1.26	100162	0.56
Std. Dev.	0.6	0.6	0.01	0.06	221	0.04	2882	0.00
CV%	3.9	0.7	11.2	8.2	2.9	2.9	2.9	0.8

Test Purpose:
M.J. Bradley Transit Bus Emissions Testing

Special Procedures:
Particulate filters were saved for later speciation by M. J. Bradley & Associates.

Observations:
Continuous LCO went out of range, using LCO bag to calculate the CO for the report. Speed sensor: We read 600 rpm at idle, which is 700 rpm. The test fuel is listed as Diesel # 1, but we are currently waiting on a fuel analysis to determine whether it was Diesel # 1 or #2.

Test Sequence Number: 3198
WVU Test Reference Number: NYCTA-5190-D1-route22

Fleet Owner Full Name	New York City Transit Authority
Fleet Address	25 Jamaica Ave.
Fleet Address (City, State, Zip)	Brooklyn NY 11207
Vehicle Type	Bus
Vehicle ID Number (VIN)	4RKMNTGA7XR833764
Vehicle Manufacturer	TMC
Vehicle Model Year	1999
Gross Vehicle Weight (GVW) (lb.)	39500
Vehicle Total Curb Weight (lb.)	30700
Vehicle Tested Weight (lb.)	32250
Odometer Reading (mile)	245
Transmission Type	Automatic
Transmission Configuration	3-Speed
Number of Axles	2
Engine Type	Detroit Diesel Corp. Series 50
Engine ID Number	04R0026444
Engine Displacement (Liter)	8.5
Number of Cylinders	4
Engine Rated Power (hp)	275
Primary Fuel	D1
Test Cycle	Route-22
Test Date	4/17/99
Engineer	Kopasko, Jim
Driver	England, Jason

Emissions Results (g/mile)						Fuel Economy		
Run Seq. No.	CO	NO_x	FIDHC	PM	CO_2	mile/gal	BTU/mile	Miles
3198-1	2.60	32.9	0.10	0.13	2506	3.84	32809	2.02
3198 Average	2.60	32.9	0.10	0.13	2506	3.84	32809	2.02
Std. Dev.	0.00	0.0	0.00	0.00	0	0.00	0	0.00
CV%	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Test Purpose:
M.J. Bradley Transit Bus Emissions Testing and cycle development.

Special Procedures:
Particulate filters were saved for later speciation by M. J. Bradley & Associates

Observations:
Using LCO bag to calculate the CO for the report. Speed sensor: We read 600 rpm at idle, which is 700 rpm. Running one cycle only to gather some representative data.

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Emissions from Buses with DDC 6V92 Engines using Synthetic Diesel Fuel

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ABSTRACT

Synthetic diesel fuel can be made from a variety of feedstocks, including coal, natural gas and biomass. Synthetic diesel fuels can have very low sulfur and aromatic content, and excellent autoignition characteristics. Moreover, synthetic diesel fuels may also be economically competitive with California diesel fuel if produced in large volumes.

Previous engine laboratory and field tests using a heavy-duty chassis dynamometer indicate that synthetic diesel fuel made using the Fischer-Tropsch (F-T) catalytic conversion process is a promising alternative fuel because it can be used in unmodified diesel engines, and can reduce exhaust emissions substantially.

The objective of this study was a preliminary assessment of the emissions from older model transit operated on Mossgas synthetic diesel fuel. The study compared emissions from transit buses operating on Federal no. 2 Diesel fuel, Mossgas synthetic diesel (MGSD), and a 50/50 blend of the two fuels. The buses were equipped with unmodified Detroit Diesel 6V92 2-stroke diesel engines. Six 40-foot buses were tested. Three of the buses had recently rebuilt engines and were equipped with an oxidation catalytic converter. Vehicle emissions measurements were performed using West Virginia University's unique transportable chassis dynamometer. The emissions were measured over the Central Business District (CBD) driving cycle.

The buses performed well on both neat and blended MGSD fuel. Three buses without catalytic converters were tested. Compared to their emissions when operating on Federal no. 2 diesel fuel, these buses emitted an average of 5% lower oxides of nitrogen (NOx) and 20% lower particulate matter (PM) when operating on neat MGSD fuel. Catalyst equipped buses emitted an average of 8% lower NOx and 31% lower PM when operating on MGSD than when operating on Federal no. 2 diesel fuel

INTRODUCTION

The Energy Policy Act of 1992 (EPACT) was enacted to stimulate the research, development, and accelerated introduction of alternative fuel technologies in the United States. The objective of EPACT is to reduce the nation's dependence on imported petroleum by pursuing renewable and domestically produced energy resources. Under EPACT, DOE has established programs to promote energy diversity and the displacement of crude oil-based motor fuels.

"Gas-to-liquids" (GTL) process technology is one promising approach for achieving energy diversity [1-7]. A brief history of the Fischer-Tropsch GTL synthetic diesel process was given in a previous paper [8]. There has been heightened interest in GTL technology in recent years, as researchers and industrial firms are demonstrating favorable production economics. GTL fuel and chemical plants are emerging in developing countries. GTL pilot plants are also being developed for remote and off-shore applications to liberate remote and stranded natural gas reserves. F-T and other synthetic diesel fuels may be economically competitive with low aromatic California diesel fuel if produced in large volumes. For a commercial-scale plant, synthetic fuel price estimates range from $20 to $25 per barrel of product [2,5-7].

Fischer-Tropsch synthetic diesel fuel is typically synthesized using a three-step procedure [2-6]. First a synthesis gas is produced from the feedstock, F-T catalysis is then used to convert this synthesis gas into liquid hydrocarbons, and finally the resulting synthetic crude is upgraded using standard hydrotreating and isomerization processes and fractionated into middle distillate fuels. This process can be used to create a variety of fuel properties depending on the process technology and streams being blended. Generally, synthetic diesel fuels have favorable characteristics for use in compression ignition engines including:

- Liquid phase at ambient conditions
- Miscible in conventional petroleum-derived diesel
- Good autoignition characteristics (cetane number of 50-75 typically)
- Low sulfur (typically less than 10 ppm)
- Low aromatics (less than 3 vol% possible)
- Energy density comparable to conventional diesel
- Fuel tank flammability similar to conventional diesel
- Suitable for use in unmodified diesel engines
- Transportable as a liquid in existing petroleum infrastructure.

Due in part to the success of previous engine and chassis based testing [9-12], synthetic diesel is being considered as a candidate fuel for the DOE/NREL Alternative Fuel Truck and Bus Evaluation Projects [13].

TEST FUELS

Three test fuels were used for the bus tests:

- Federal (49-state) no. 2 diesel fuel
- 100% Mossgas synthetic diesel with fuel lubricity additive
- 50:50% Mossgas synthetic diesel:Federal no. 2 diesel with fuel lubricity additive

The synthetic diesel fuel for this study was produced using the Mossgas conversion of olefins to distillate ("COD") process. Mossgas produces a range of automotive fuel products and chemicals using a natural gas feedstock obtained by pipeline from their off-shore production platform in Mossel Bay, South Africa. The natural gas is reformed to synthesis gas consisting of hydrogen and carbon monoxide. The synthesis gas is chemically converted using high temperature Fischer-Tropsch catalysis to produce olefins and automotive fuel components for commercial markets.

The light olefins that remain from the Fischer-Tropsch conversion, such as propene, butene, pentene and hexene, were used to synthesize the test fuel used in th study. These light olefins were catalytically oligomerizec over a zeolite catalyst to form gasoline and distillate. The resulting product was then hydrotreated. Mossgas uses the COD process to produce commercial specialty fuels and blendstocks.

The properties of the Mossgas synthetic diesel fuel and the Federal no. 2 diesel fuel used in this study are shown in Table 1. The Mossgas fuel had no detectable sulfur, and a cetane number of about 50. The aromatic content was 10% by volume, which is higher than that of a typica Fischer-Tropsch diesel. The cold flow properties of the Mossgas fuel were excellent with a pour point and clouc point below –60 degrees Celsius. A commercially available lubricity improver (Paradyne 655 at 200 ppm treat rate) was added to meet acceptable lubricity levels.

The Federal no. 2 diesel used in the study had a relatively low sulfur content of 0.02% by weight. This is much lower than the standard of 0.05% and lower than the 0.03% to 0.035% sulfur content typically found in Federal diesel.

VEHICLE TESTING

TEST VEHICLES – The buses used for the testing were loaned to the project by the Port Authority of Allegheny County ("PaTransit"). They were removed from revenue service in Pittsburgh, PA for the emissions measurements. The 40-foot buses were 1991 model year made by Orion Bus Industries and equipped with 1991 model year Detroit Diesel Corporation (DDC) 6V92 two-stroke diesel engines. One of the test buses is shown in Figure 1.

Figure 1: One of the Pittsburgh transit buses used for the emissions measurements.

Table 1: Test Fuel Properties

Analysis	ASTM	Units	100% MGSD (Mossgas Data) [14]	100% MGSD (SwRI Data) [15]	Federal Diesel Fuel [16]
Flash Point	D93	°C	100	97	
Cloud Point	D2550	°C		<-60	
Water content	D1744	vol%	0.01		
Sediment by extraction	D473	mass%	<0.01		
Water and Sediment	D1796	vol%		0	
Carbon Residue on 10% residue	D4530	wt%	0.09		
Carbon Residue on 10% distillation residue	D524	%		0.1	
Ash	D482	wt%	<0.01		
Distillation	D86	°C			
IBP				229.9	188
10%				235.3	212
50%				254.7	256
90%			321.1	323.7	307
FBP			360.8	361.2	331
Kinematic Viscosity	D445	cSt @ 40°C	2.974	2.98	
Sulfur	D2622	mass%	<0.001		
Sulfur	D5453	ppm		<5	
Sulfur	D4294	wt%			0.02
Corrosion, 100°C for 3 hours	D130	Rating	1A		
Cetane Number	D613		51.4	48.9	
Cetane Index	D4737				48.7
Density @ 20°C	D4052/ D1298	kg/l	0.8007	0.8042	
API Gravity @ 15.6°C	D287	°API		44.0	37.4
Cold Filter Plugging Point	IP309	°C	<-35		
Pour Point	D97	°C		<-60	
SFC Aromatics	D5186	mass%			
Total Aromatics				9.18	
PNA				0.21	
FIA	D1319	vol%			
Aromatic					24.7
Olefins					1.5
Saturate					73.8
Aromatics	IP391	vol%	10.1		
Gum Content	D381	mg/l00ml			
Unwashed				8.8	
Washed				0.4	
Lubricity SLBOCLE	D6078	grams			
Neat Fuel				1950	
With Paradyne additive				3800	
Lubricity HFRR	D6079	micron			
Neat Fuel				600	
With Paradyne additive				255	
Oxidation Stability	D2274	mg/100 ml	0.3		
Carbon/Hydrogen	D5291	mass%			
Carbon				83.98	86.11
Hydrogen				14.43	13.37
Nitrogen					<0.03
Residual					
Oxygen (by diff)				1.59	
Heat of Combustion	D240	Btu/gal			
Gross				134,712	137,609
Net				125,878	129,147

The DDC 6V92 is a 2-stroke, vee-configuration, 6 cylinder, 9.05 liter, turbocharged and aftercooled diesel engine with electronic unit fuel injectors. The Pittsburgh bus engines were rated to 253 horsepower (at 2100 rpm) and 880 ft-lb of torque (at 1200 rpm).

Three of the six buses used in this study used engines with high mileage accumulation (typically over 350,000 miles) and were not equipped with exhaust gas aftertreatment. The other three buses had engines that were recently rebuilt according to the Environmental Protection Agency's Urban Bus Retrofit/Rebuild Program and were fitted with an oxidation catalytic converter manufactured by Engine Control Systems Ltd. Bus number 2029 was tested early in the study without a catalyst. It was then fitted with a rebuilt engine and a catalytic converter and retested. The test buses were not modified in any way for the Mossgas synthetic diesel fuel.

CHASSIS EMISSIONS TESTING - West Virginia University (WVU) measured emissions for this study using one of its transportable emissions laboratories located at the WVU home site in Morgantown, WV. The transportable laboratory consists of a heavy-duty chassis dynamometer and an emissions measurement facility. Design details of the laboratory and previous emissions measurements using the laboratory have been presented in several previous reports [17-25].

<u>Chassis Dynamometer</u> – The dynamometer equipment is mounted on a fifth wheel semi-trailer for portability. Upon arriving at the test site, the wheels of the trailer are removed and the trailer is lowered to the ground. The test vehicle is driven onto two sets of free running rollers mounted in the trailer bed. Power is transferred from the test vehicle to the dynamometer through hub adapters that are bolted to the drive wheels. The inertia weight of the bus is simulated by a set of flywheels. The road load is applied to the test vehicle using air-cooled eddy current power absorbers. Figure 3 shows one of the test buses mounted on the dynamometer.

<u>Emissions Measurements</u> – The emissions measurement system uses a 45.7 cm (18 in.) diameter, 6.1 m (20 ft.) long exhaust dilution tunnel mounted atop the box trailer that houses the emissions measuring equipment. Two fans and critical flow venturis control the flow rate in the dilution tunnel.

Carbon monoxide (CO), carbon dioxide (CO_2), oxides of nitrogen (NO_x), and total hydrocarbons (THC) are measured continuously throughout the test. Particulate matter (PM) is captured on a filter and weighed. Bag samples are collected and analyzed for background correction.

<u>Test Method</u> – The buses were tested using the Central Business District (CBD) driving cycle described in SAE Recommended Practice J1376. The CBD driving cycle was developed by the Federal Transit Administration to represent the operation of a transit bus in a downtown business district. The cycle, shown in Figure 4, consists of

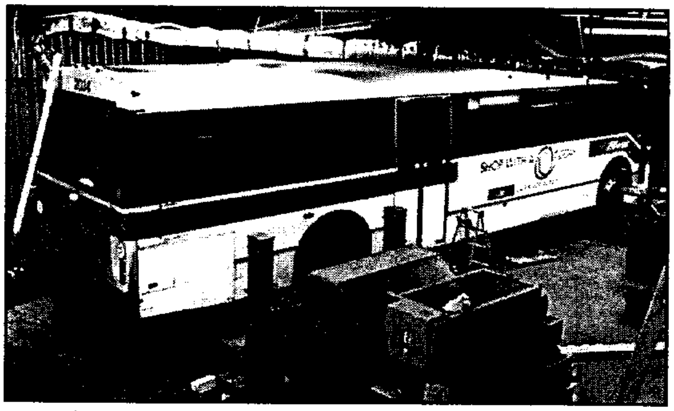

Figure 3: One of the PaTransit buses on the WVU transportable chassis dynamometer

fourteen identical acceleration, cruise, and deceleration cycles. A short idle time was added before and after the vehicle activity to aid data gathering in the light of sampling delay times [26]. The cruise sections occur at 32 km/hr (20 mph). Transit bus emissions measurements using this driving cycle have been reported in many previous papers [for example, 22, 27-29].

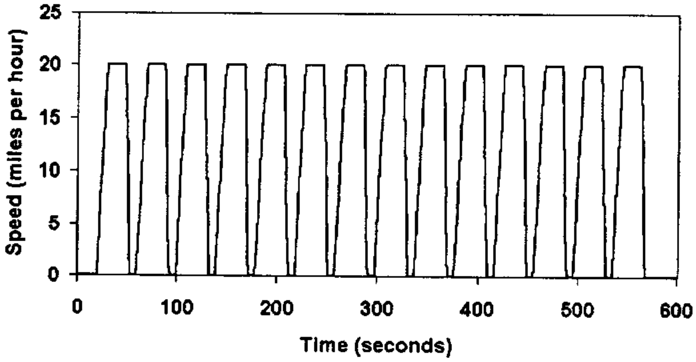

Figure 4: The Central Business District (CBD) driving cycle.

<u>Tests Performed</u> – Three buses with rebuilt engines and equipped with catalytic converters and three buses without catalytic converters were tested. The emissions from each bus were measured while the bus operated on each of the three test fuels. Between measurements with different fuels, the bus' fuel system was emptied and flushed with the new fuel type. The emission tests performed are summarized in Table 2.

Table 2: Summary of Emissions Tests Performed

	Fuel	Number of Tests
Buses **with** rebuilt engines and catalytic converters	No. 2 Diesel	3
	100% MGSD	3
	50% MGSD	3
Buses **without** catalytic converters	No. 2 Diesel	3
	100% MGSD	3
	50% MGSD	3
		Total = 18

RESULTS

Drivers could not detect a performance difference between buses operating on the Mossgas synthetic diesel and the Federal no. 2 diesel fuel over the CBD driving cycle. The average emissions results are summarized in Table 3. At least three measurements were taken and averaged for each result presented in the table.

EFFECT OF TEST FUEL - Three buses equipped with rebuilt engines and catalytic converters were tested on the three test fuels. The results of these tests are shown in the bar charts of Figure 5. Each chart shows results for each bus and the average of all three buses. Substituting 100% MGSD fuel in place of no. 2 diesel fuel led to lower average levels of all four emissions measured. NO_x was reduced by an average of 8%, PM was reduced by an average of 31%, CO was reduced by an average of 49%, and HC was reduced by an average of 35%. The average NO_x reduction with a 50:50 blend of no. 2 diesel and MGSD was substantially more than half of the reduction with 100% MGSD fuel. The PM reduction with the blend was approximately half of the reduction measured with 100% MGSD fuel.

With the exception of the hydrocarbon emissions from bus 2029, all buses followed the same trend of progressively decreasing emissions with 50% and 100% Mossgas synthetic diesel.

Table 3: Average emissions (in grams per mile) and fuel mileage from buses tested on federal No. 2 diesel, Mossgas synthetic diesel (MGSD) , and a 50:50 blend of the two fuels.

	Fuel	Bus Number	CO	NO_X	HC	PM	CO_2	MPG*	Btu/mile
Buses **with** rebuilt engines and catalytic converters	No. 2 Diesel	2025	1.96	34.51	0.75	1.23	4355	2.33	55713
	No. 2 Diesel	2029	1.07	26.91	0.39	1.89	4458	2.28	56995
	No. 2 Diesel	2048	2.11	29.71	0.75	1.12	3451	2.94	44159
	Averages:		**1.71**	**30.38**	**0.63**	**1.41**	**4088**	**2.52**	**52289**
	50% MGSD	2025	1.34	31.93	0.54	1.14	4360	2.20	57589
	50% MGSD	2029	0.81	26.40	0.40	1.59	4346	2.21	57391
	50% MGSD	2048	1.51	27.69	0.59	0.83	3381	2.84	44672
	Averages:		**1.22**	**28.67**	**0.51**	**1.19**	**4029**	**2.42**	**53217**
	100% MGSD	2025	1.02	31.37	0.44	1.01	4206	2.19	56272
	100% MGSD	2029	0.75	26.10	0.29	1.16	4181	2.21	55928
	100% MGSD	2048	0.82	26.53	0.49	0.76	3338	2.77	44659
	Averages:		**0.87**	**28.00**	**0.41**	**0.97**	**3908**	**2.39**	**52286**
Buses **without** catalytic converters	No. 2 Diesel	2029	11.73	35.85	1.82	1.79	4328	2.34	55598
	No. 2 Diesel	2030	6.65	34.88	2.11	1.18	4149	2.44	53221
	No. 2 Diesel	2034	40.42	26.26	1.31	9.03	4900	2.05	63468
	Averages:		**19.60**	**32.33**	**1.75**	**4.00**	**4459**	**2.28**	**57429**
	50% MGSD	2029	10.33	32.23	1.88	1.52	4348	2.20	57601
	50% MGSD	2030	6.26	33.93	2.03	1.13	4099	2.34	54244
	50% MGSD	2034	37.91	26.02	0.99	8.61	4704	2.02	62887
	Averages:		**18.16**	**30.72**	**1.63**	**3.75**	**4383**	**2.18**	**58274**
	100% MGSD	2029	11.02	33.37	1.72	1.34	4392	2.09	58963
	100% MGSD	2030	5.73	32.92	1.75	1.16	4133	2.23	55391
	100% MGSD	2034	26.52	25.64	0.72	7.07	4639	1.97	62596
	Averages:		**14.42**	**30.64**	**1.40**	**3.19**	**4388**	**2.10**	**58984**

* Miles per liquid gallon (not corrected for energy content)

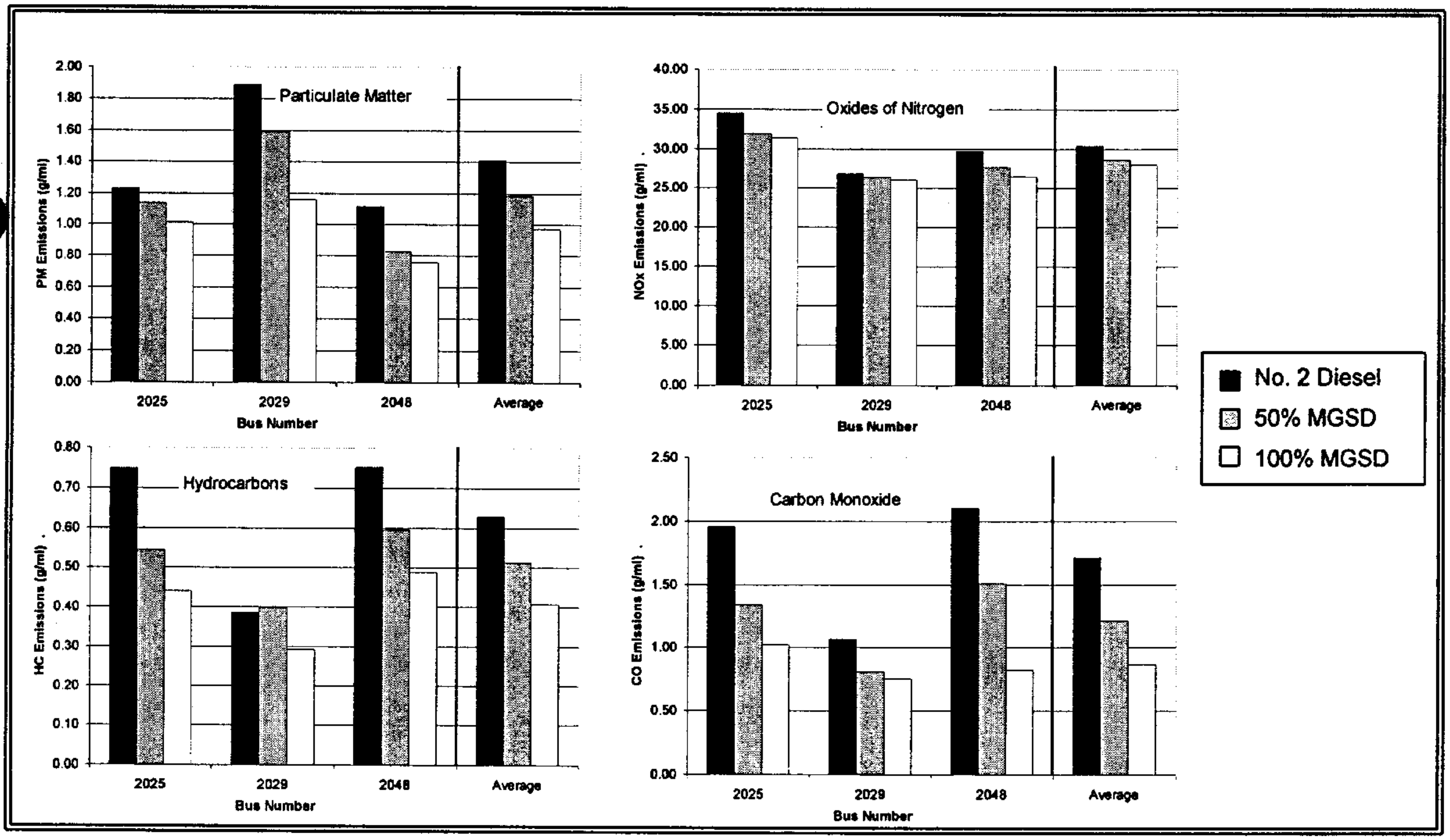

Figure 5: Emissions results from buses **with** rebuilt engines and catalytic converters

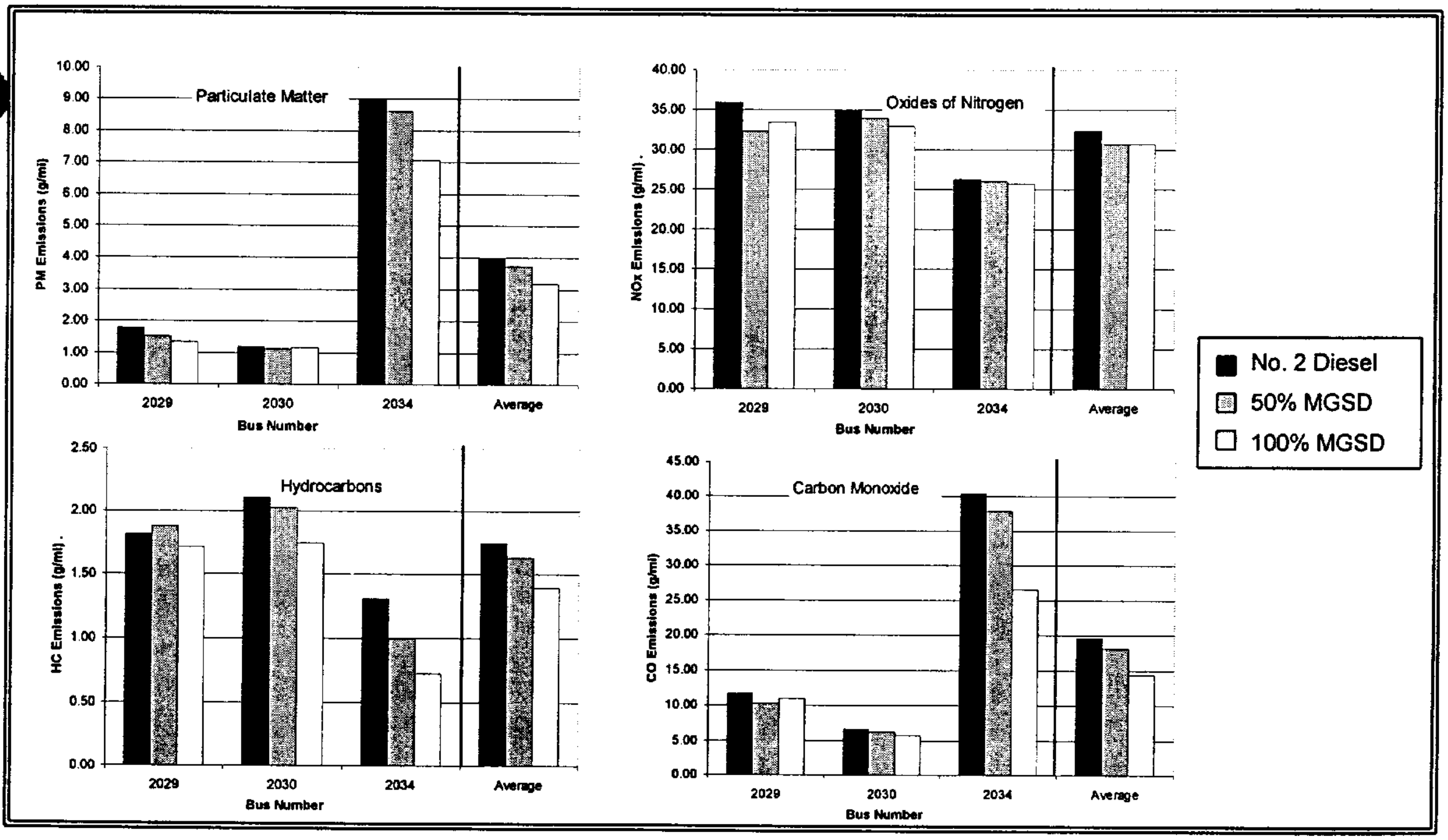

Figure 6: Emissions results from buses **without** catalytic converters

Three buses with high mileage engines and no catalytic converters were also tested. The results of these tests are shown in the bar charts of Figure 6. Substituting 100% Mossgas synthetic diesel fuel in place of Federal no. 2 diesel fuel in these buses also led to lower average levels of all four emissions measured. NO_x was reduced by an average of 5%, PM was reduced by an average of 20%, CO was reduced by an average of 26%, and HC was reduced by an average of 20%. In this case, The average NO_x reduction with a 50:50 blend of no. 2 diesel and MGSD was nearly identical to the reduction with 100% MGSD. This result agrees with an earlier study by the authors on class 8 trucks using Shell Middle Distillate F-T fuel [8]. In contrast, the PM reduction with the blend was only about a quarter of the reduction measured with 100% MGSD fuel.

Bus number 2034 had dramatically higher PM and CO emissions and somewhat lower NOx and HC emissions than buses 2029 and 2030. Although buses 2029 and 2030 had similar fuel consumption (within about 4%), the fuel consumption of bus 2034 on Federal no. 2 diesel was somewhat higher (about 16% higher than the average of buses 2029 and 2030). The higher fuel consumption and lower NOx indicates that the injection timing in bus 2034 may be retarded relative to manufacturer specifications. Note that much of the average PM reduction with MGSD in this set of buses is due to the large reduction in PM from bus 2034.

When tested on 50% MGSD, the emissions trends of bus number 2029 (without a catalyst) were different than the other two non-catalyst buses for NOx, HC, and CO. These trends can be seen clearly in Figure 6. The cause of this anomaly is unknown.

EFFECT OF REBUILT ENGINES AND CATALYST - The average emissions from buses with rebuilt engines and catalytic converters are compared to emissions from buses with older engines and no catalytic converters in Figures 7 and 8. The buses with rebuilt engines and catalysts had dramatically lower CO, HC and PM emissions than those with older engines and no catalyst. Most of this reduction is likely due to the oxidizing effect of the catalyst on CO, HC, and the soluble organic fraction of the PM emissions.

Also apparent from Figures 7 and 8 is that NOx emissions were reduced somewhat in the buses with rebuilt engines and catalytic converters. The NOx reduction cannot be attributed to the catalyst. The emission reductions from buses with rebuilt engines and catalysts followed the same trends in all buses with both MGSD and Federal no. 2 diesel.

Continuous gaseous emission rates were measured during the tests. Although not directly relevant to the comparison of fuels, an interesting trend in the continuous data warrants mentioning. Buses with oxidation catalytic converters had decreasing HC and CO emissions over the course of the CBD test cycle. Typical continuous HC and CO for a catalyst-equipped bus are shown in Figures 9

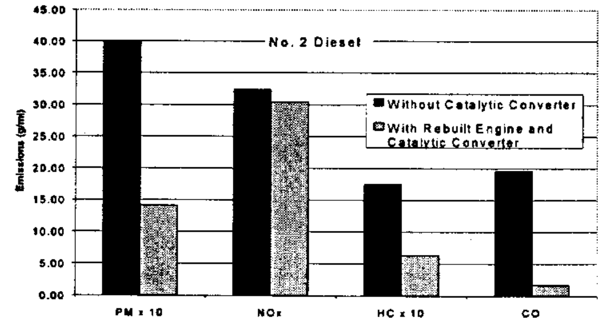

Figure 7: Average emissions results from buses with rebuilt engines and catalytic converters compared to buses without catalytic converters while operating on no. 2 diesel fuel.

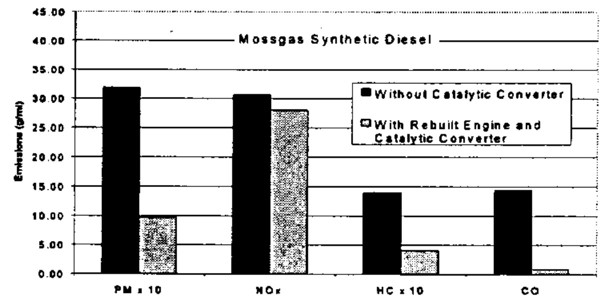

Figure 8: Average emissions results from buses with rebuilt engines and catalytic converters compared to buses with out catalytic converters while operating on Mossgas synthetic diesel fuel.

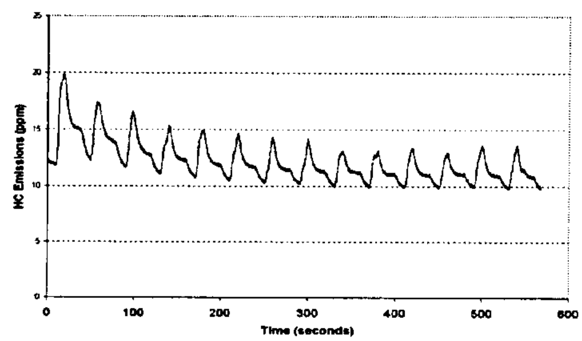

Figure 9: Continuous HC emissions over the CBD cycle from a bus with rebuilt engine and catalytic converter.

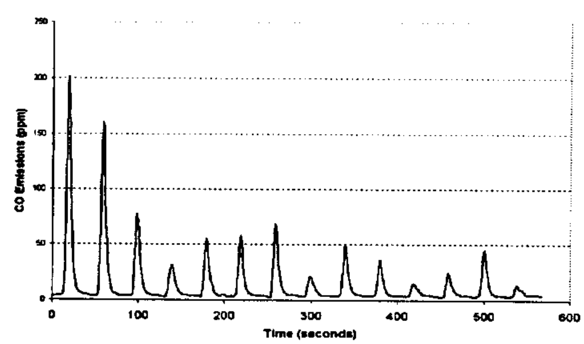

Figure 10: Continuous CO emissions over the CBD cycle from a bus with rebuilt engine and catalytic converter.

and 10. This trend was not observed in buses without catalysts.

Figures 9 and 10 clearly illustrate that the HC and CO drop progressively over the cycle. The WVU protocol for the CBD test cycle includes three additional peaks of the CBD just prior to the actual test data shown here, so the catalyst has already seen some exhaust warming. These results indicate that a test facility that did not employ the warm-up ramps would see higher average HC and CO emissions than measured in this study. This suggests a need for more precisely defined heavy duty vehicle chassis testing protocols to avoid measurement differences between facilities.

FUEL CONSUMPTION – For each of the buses tested, the fuel consumption (in Btu/mile) was not strongly affected by the fuel type. No more than a 3% deviation from the average fuel consumption occurred on any bus. The trends in this small variation were mixed – the MGSD lead to higher fuel consumption in four buses and lower fuel consumption in two buses. The bus-to-bus variability was much greater than the fuel effect. Fuel consumption of no. 2 diesel fuel differed by as much as 23% between catalyst equipped buses and 16% between buses without catalysts.

CONCLUSIONS

- The use of Mossgas synthetic diesel fuel and the use of rebuilt engines and catalysts according to the EPA Urban Bus Retrofit/Rebuild Program both show promise for reducing emissions from older transit buses using Detroit Diesel 6V92 engines.
- The Mossgas synthetic diesel fuel had properties conducive to low emissions, including no detectable sulfur, and an aromatic content of about 10% by volume. The Mossgas synthetic diesel also had excellent cold flow properties.
- Drivers could not detect a performance difference between buses operating on the Mossgas synthetic diesel and the Federal no. 2 diesel fuel over the CBD driving cycle.
- Use of Mossgas synthetic diesel in place of Federal no. 2 diesel in the test buses led to lower levels of all four regulated emissions measured. For the buses with rebuilt engines and oxidation catalytic converters, oxides of nitrogen were reduced by an average of 8%, particulate matter was reduced by an average of 31%, carbon monoxide was reduced by an average of 35%, and total hydrocarbon emissions were reduced by an average of 49%.
- The variation of fuel consumption with test fuel was less than 3% and was much smaller than the bus-to-bus fuel consumption variation.
- More precisely defined heavy-duty vehicle chassis dynamometer testing protocols are needed to avoid measurement differences between facilities due to catalyst warm-up.

ACKNOWLEDGMENTS

The authors would like to extend special acknowledgment to Mossgas (Pty) Ltd for their participation and expert contribution to this study. We would also like to acknowledge the support and hard work of all of those involved in the transit bus evaluation project, the emissions measurement effort, and the procurement and analysis of Mossgas synthetic diesel fuel: Mike Frailey, NREL; Kevin Chandler, Battelle; Karen Kohl, Southwest Research Institute; the Port Authority of Allegheny County; Byron Rapp, James Kopasko, and Wenwei Xei, West Virginia University; and the West Virginia University laboratory staff.

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DEFINITIONS, ACRONYMS, ABBREVIATIONS

CBD – Central Business District (driving cycle)
CO – Carbon Monoxide
COD – Conversion of Olefins to Distillate
DDC – Detroit Diesel Corporation
DOE – U.S. Department of Energy
EPA – Environmental Protection Agency
EPACT – Energy Policy Act of 1992
FBP – Final Boiling Point
FIA – Fluorescent Indicator Adsorption
F-T diesel – Fischer-Tropsch diesel
FTP – Federal Test Procedure
GTL – Gas-to-liquids
HC – Hydrocarbons
HFRR – High Frequency Reciprocating Rig
IBP – Initial Boiling Point
MGSD – Mossgas synthetic diesel
NO_x – Oxides of Nitrogen
NREL – National Renewable Energy Laboratory
PM – Particulate Matter
ppm – parts per million
SFC – Supercritical Fluid Chromatography
SLBOCLE – Scuffing Load Ball On Cylinder Lubricity Evaluator
THC – Total Hydrocarbons
WVU – West Virginia University

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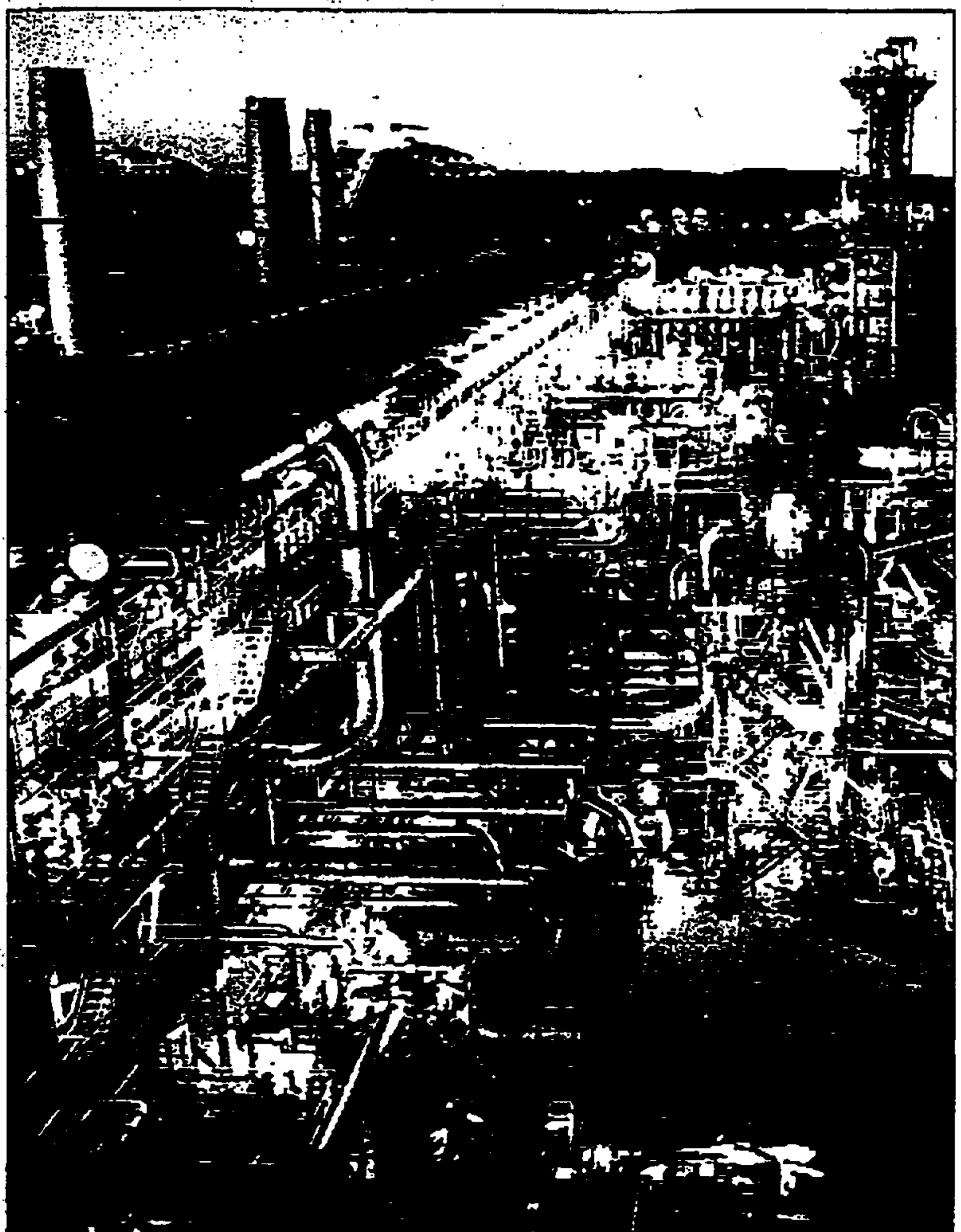

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QUARTERLY

Converting olefins to diesel — the COD process

Many refiners are looking for more flexible processes for upgrading olefins from different sources. A new zeolite-based process has had its first application at a refinery in South Africa.

E Köhler F Schmidt H J Wernicke : *Süd-Chemie AG*
M de Pontes and H L Roberts : *CEF*

Today the process used most for conversion of olefins into fuels is oligomerisation with phosphoric acid catalysts. However, the polygas process produces mainly fuels in the gasoline range. Moreover, the catalyst is not regenerable and disposal may become a concern in the long-term future. A new zeolite-based process for converting olefins to diesel (COD process) has been selected by the Mossgas Refinery in the Republic of South Africa. The major advantage of the process is its great yield flexibility. Although the South African feedstock is of Fischer-Tropsch origin, the process is widely applicable to olefins of varying carbon numbers.

Zeolite catalysts have been widely used in oil refining for the past two decades. Examples of successful commercial applications are the alkylation of benzene with ethylene, xylene isomerisation, M-forming, selectoforming of reformate gasoline, dewaxing of gasoils and lubeoils and the conversion of methanol to gasoline (MTG) – a majority of them using pentasil and mordenite catalysts or catalysts derived from these species.

Süd-Chemie with CEF of South Africa has now developed a proprietary catalyst to convert olefins into gasoline and diesel in the first such commercial plant to be built in the world.

Fuel quality. The ignition performance of diesel fuels is characterised by the cetane number. Thus, the value of a given diesel is determined by its components. Normal paraffins, for example, have high cetane numbers and aromatics have low ones.

Diesel fuels must also comply with such other specifications as cold flow properties, which are determined by those branched paraffins that do not tend to crystallise so readily as do normal paraffins. High-octane gasoline should be primarily based on branched products (paraffins as well as olefins) and aromatics. These ingredients must, of course, be balanced to comply with modern industrial standards as well as increasingly stringent legislation.

To meet requirements for alternative production modes, the olefin oligomerisation catalyst needs much flexibility and, even more, a combination of specific properties such as high oligomerisation activity via acid catalysis; shape selectivity to produce mainly paraffins (after hydrogenation), a good proportion of which is straight chain or low-branched; low activity for ring forming – the formation of aromatics in the diesel fraction; and shape selectivity for isomerisation and cracking along with hydrogen transfer and aromatics formation in the gasoline fraction.

It transpired that these characteristics are best achieved by a shape-selective zeolite catalyst. Hence development of the COD catalyst.

The basis for the success of the COD catalyst is a combination of catalytically favourable properties such as well-defined crystalline structure and crystallite size, uniform pores, high internal surface area, ability to absorb specific molecules, balanced Lewis/ Brönstedt acidity, high thermal stability and long cycles and catalyst life.

Acidity. The number and strength of the acid sites is related to the zeolite framework in so far as Brönstedt acid sites are associated with the presence of framework aluminium atoms. To get properly balanced oligomerisation and cracking activity it is necessary to adjust the number and strength of the acid sites to the needs of the COD process. In this respect the Si/Al ratio of the zeolite and binder system are of fundamental importance.

Shape selectivity. Selectivity of shape results from intimate interactions of dimensions and geometry of the zeolite's channels with the size, shape and configuration of the molecules taking part in a reaction. The COD catalyst provides pore dimensions capable of absorbing, in order of preference, normal, iso- and monomethyl-substituted alkanes and alkenes as well as single-ring aromatic hydrocarbons.

The literature distinguishes between three different kinds of shape selectivity that clearly all play a certain role in the COD process: product shape selectivity (PSS), reactant shape selectivity (RSS) and restricted transition state selectivity (RTSS). While RSS and PSS affect in particular the ratio of branched to straight chain hydrocarbons, the high selectivity to olefins in the diesel mode can be attributed to the RTSS mechanism – apart from process conditions in favour of suppression of H_2 transfer and cyclisation.

Moreover, because of RTSS the COD catalyst is much less prone to deactivation by coke formation than are conventional catalysts, since it prevents formation of coke precursors.

The COD process takes full advantage of shape selectivity insofar as hydrocarbons resulting from oligomerisation and cracking are predominantly restricted either to the diesel or gasoline range, depending on process conditions. Basic characteristics of olefin oligomerisation are that high pressure favours oligomerisation and maximum distillate yield while higher temperatures promote through hydrogen transfer the formation of branched paraffins and aromatics, both being the basis for high-octane gasoline.

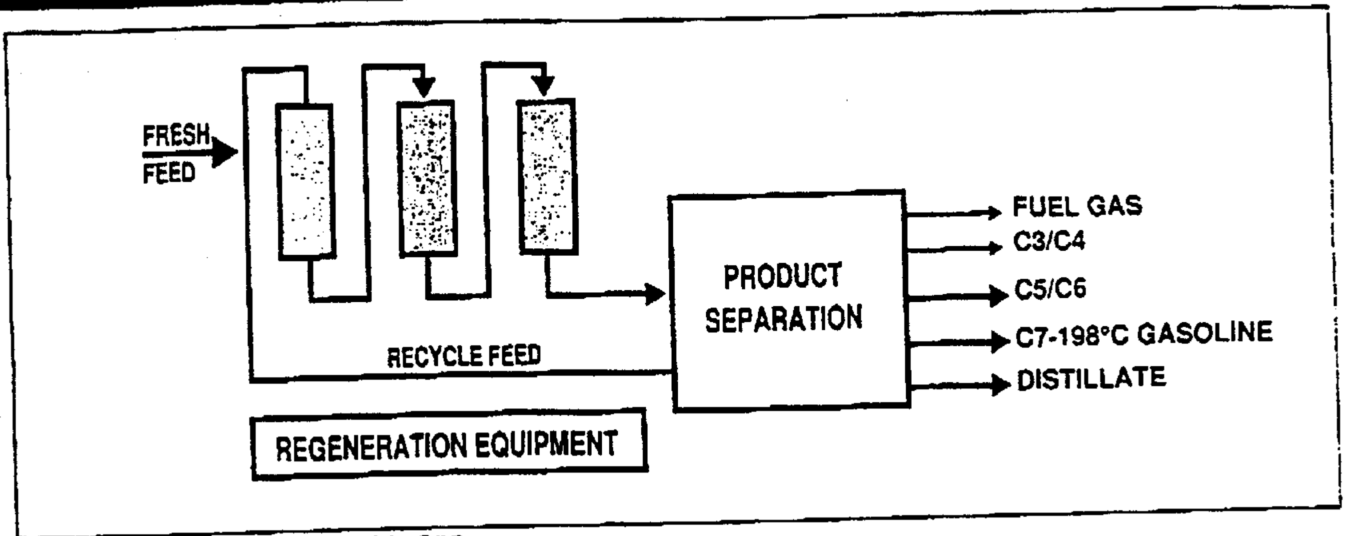

Figure 1. Schematic representation of the COD process.

Catalyst development and scale-up. The COD catalyst is an example of how closely interlinked process engineering and catalyst development can shorten the time to commercialisation. Catalyst development started in 1988 and the engineering and construction of a new grass-roots zeolite plant was finalised by the end of 1990. Soon afterwards the zeolite catalyst manufacture was running at full capacity.

The COD process. The COD process, which oligomerises olefins into diesel and gasoline, can be varied to maximise either diesel or gasoline yield. Liquid fuel yield, based on olefins, is 97 per cent by mass. The commercial plant converts a feed rich in olefins into diesel that has a high cetane number, is sulphur-free and has a small amount of aromatics.

The plant, which started in 1992, has a throughput of 68 tonnes an hour. The maximum distillate mode yields 78 per cent distillate and 19 per cent gasoline.

Process development. In tandem with the catalyst development, CEF of South Africa and Lurgi of Germany started development of the COD process. The programme involved testing, in a process development unit with industrial feedstock, a variety of catalyst formulations. Simultaneously, process parameters were systematically studied.

To prove scale-up, a demonstration plant was constructed for the process. This plant ran so as to demonstrate the viability of the process and provide diesel and gasoline fuel samples for motor trial tests. Tests were conducted under process conditions that maximised diesel yield (the maximum distillate mode), and under other process conditions that maximised gasoline yield. Finally, the process development unit was run under process design con-

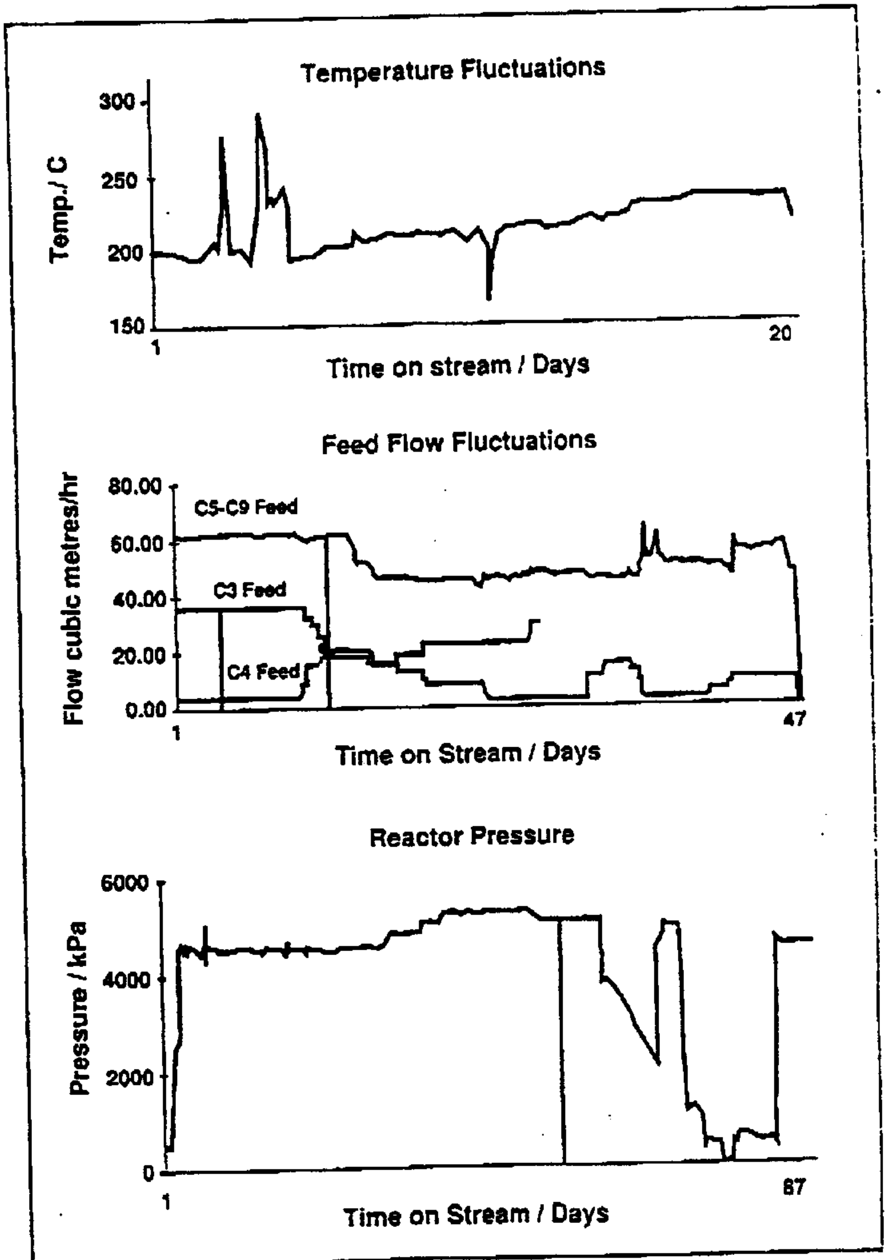

Figure 2. COD plant upsets without effect on catalyst and process.

ditions, with commercial feedstock, for the guaranteed catalyst lifetime.

Feedstocks. The COD process and catalyst were designed to tolerate a feedstock that has a variety of hydrocarbon oxygenates, including alcohols, acids, esters and ketones. Typical composition of such a feed is as follows:

Component	*Wt%*
Olefins	81.7
Paraffins	15.0
Aromatics	1.5
Oxygenates	1.8

The oxygenates have a considerable effect on catalyst cycle time, as their presence causes premature catalyst deactivation. Process parameters were tailored to maximise cycle length.

Included in the feed shown above is a stream that is saturated with water. Other process tests were carried out with feedstocks that do not have the oxygenate components, in which cases the catalyst cycle lengths were substantially extended.

The first commercial plant of its type in the world was selected by Mossgas, South Africa, to convert lower olefins into liquid fuels. Lurgi was awarded the project, which began in 1990 and was completed in 1992. The plant was successfully commissioned in late 1992 and has been operational since then.

Figure 1 is a schematic representation of the COD plant indicating that product separation can be tailored to clients' requirements. The fuel gas stream is small; the C_3 stream is chiefly propane coming from the feed. The C_4 stream, though small, contains all the butane from the feed as a major component, with most of the unreacted butene in the form of isobutene. The catalyst is regenerated in situ, and the catalyst cycle time turned out to be much longer than originally expected. The catalyst has not yet reached the end of its life.

The robustness of the plant design has allowed for unexpected pressure and feed fluctuations as well as for on-line maintenance. Figure 2 shows upset conditions as they occurred on the commercial plant. In all cases, once the upset conditions had been corrected the product yield and qualities returned to design specifications, and it was not necessary for the plant to come off-line. The temperature upset occurred as a result of recycle pump problems, though there was no effect on the catalyst or the process. The feed flow fluctuations were caused by upstream storage-tank problems, and during this time the only operating parameter adjusted was reactor temperature, to maintain conversion and product qualities.

The pressure changes resulted from a faulty pressure relief valve, which was repaired (at about 60 days) and then run for a week longer. The low pressures shown were regeneration pressures. At 80 days a new catalyst cycle started.

Liquid fuel products. The COD process produces diesel (after hydrogenation) that is particularly suited to modern environmental legislation: high cetane, sulphur-free and very low aromatics content. Tests are being done for diesel that can operate in extreme climatic conditions. Table 1 gives measured properties of the hydrogenated diesel product produced from the feedstock shown in the example above.

The gasoline has a research octane number (RON) of between 81 and 85. The motor octane number (MON) is between 74 and 75.

Plant operation. The utility and manpower requirements for the COD plant, including downstream distillation columns, are comparable with those of any other refinery unit. Utility requirements for a 67.5 tonnes/h feed

SOUTH AFRICAN INSTITUTE OF TRIBOLOGY

"LIQUID FUELS"

OIL DEGRADATION IN LIGHT COMMERCIAL VEHICLES IN SOUTHERN AFRICA

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ABSTRACT

Rapid engine oil degradation in diesel fuelled, light commercial vehicles in South Africa has restricted oil drain intervals to 5 000 km or less. These vehicles are predominantly equipped with Japanese high speed, naturally aspirated, indirect-injection (IDI) engines. The limited oil drain interval is seen as a major problem in the subcontinent where large distances are travelled.

To address this problem Caltex Oil (SA) (Pty) Ltd., the Centre for Automotive Engineering of the University of Stellenbosch (CAE), Daimler-Chrysler South Africa (DCSA) (then Mercedes-Benz of South Africa (Pty) Ltd. (MBSA)) and Mossgas (Pty) Ltd. collaborated in a project to investigate oil degradation. The objective of the investigation was to determine the effect of fuel and lubricant properties on oil drain interval.

The project was initiated with a series of road tests under typical driving conditions in which engine parameters were recorded. The road test data was used as the basis for the development of an engine bench dynamometer test cycle which was reproducible and accelerated the degradation of the engine oil.

A 2.5 litre Mitsubishi Colt engine (4D56) was mounted on an engine test bench and run for a total of 940 hours on the developed test cycle. The objective of the initial tests was to enable the identification of the mechanisms causing oil degradation and the rate thereof. This was achieved by regular sampling and extensive oil analysis. It was found that the oil degradation was in the form of excessive viscosity increase, primarily as a result of high soot contamination; and to a lesser extent as a result of oxidation and the loss of lighter fractions.

To confirm the laboratory observations and to correlate test hours in the laboratory with mileage on the road, a series of tests were conducted in a controlled vehicle fleet. These vehicles operated under a number of different workloads, which enabled the effect of variations in operating conditions to be gauged. The mechanism of degradation in the field test was found to be identical to that observed in the laboratory. It was also found that the oil degradation was closely linked to vehicle fuel consumption.

It was evident that the additive package in a lubricant has a significant effect on its ability to carry large quantities of soot without suffering from excessive viscosity increase. The sulphur content of the fuel was also found to have a significant effect on the rate of oil degradation which justifies further investigation into the benefits of reduced sulphur levels in local fuel.

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INTRODUCTION

Rapid oil degradation in the engines of diesel fuelled light commercial vehicles in Southern Africa has restricted the oil drain interval to 5000 km, and 3500 km in severe operating conditions. The problem has resulted in considerable down time for fleet owners; to the extent that additional vehicles can be required in order to maintain the productivity of fleets. The oil drain interval of equivalent petrol vehicles is 10 000 km and thus the problem of rapid oil degradation significantly erodes any benefits that can be derived from the use of diesel engines. Extending the oil drain interval of the fuel efficient diesel vehicles is thus a high priority to justify the increased initial purchase cost relative to the cheaper petrol vehicles.

This problem prompted Caltex Oil (SA) (Pty) Ltd., the Centre for Automotive Engineering of the University of Stellenbosch (CAE) and Daimler-Chrysler South Africa (Pty) Ltd. (DCSA) to collaborate in a lubricant research project. The first objective of this project was to identify the causes of the limited oil drain intervals, and secondly to find suitable oils to enable oil drain intervals to be extended. At the end of this project, a further study was conducted into the effect of fuel sulphur content in diesel, with the support of Mossgas.

Road tests were carried out on a one ton commercial pickup truck equipped with a Mitsubishi 4D56 engine (Japanese, 2.5 litre, indirect injection (IDI), light delivery vehicle) during which typical and extreme engine utilisation was measured [1]. Thereafter a Mitsubishi 4D56 engine was installed on an engine test bench to enable the development of an extreme, yet representative test cycle for the evaluation of lubricants under controlled conditions. The test procedure was then used to identify oils that were suitable for use during an extended oil drain interval under South African conditions. Road tests, which were completed over a total distance of more than 250 000 km, were used to confirm the results obtained from engine testing done in the laboratory.

ENGINE OIL DEGRADATION

Oil Degradation Mechanisms

Some of the basic functions of a diesel engine lubricant are to reduce friction and prevent wear, but additionally they must be able to control deposits (such as soot) and resist breakdown and thickening in service [2]. Engine oils are formulated to resist a variety of different degradation mechanisms which are typically classified in three categories [2] [3]:

Contamination By Combustion Products

Soot, which is formed in the engine during the combustion process, is deposited in the engine oil by the blowby gases leaking past the piston rings. This soot then contributes to sludge formation in the engine oil and subsequently an increase in viscosity [4]. Sludging as a result of excessive soot contamination of the lubricant was found to be the dominant mechanism of oil degradation in light commercial diesel vehicles in Southern Africa [1]. There are a variety of causes of excessive soot formation in a diesel engine [5], namely:

Improper combustion - Overfueling is the main cause of the formation of soot during the combustion process. This occurs when the engine is unable to burn effectively all the fuel that is injected into the combustion chamber. Improper injector nozzle operation causes inadequate fuel atomisation, also leading to improper combustion [6].

Limited oxygen in the combustion chamber - This condition can occur at high altitudes or when driving with a blocked or restricted air filter. This is a particular problem in South Africa, due to the high levels of atmospheric dust coupled with the fact that a large part of the country is higher than 1 300 meters above sea level.

Oxidation

Oxidation is the degradation of the base oil, mainly caused by thermal stress and is accelerated by the depletion of antioxidants in the additive package. It occurs primarily as a result of the reaction between the hot lubricant and a combination of air, combustion by-products and unburned fuel [7]. While oxidation also leads to an increase in the viscosity of oils [5], it was not found to be a major contributor to the viscosity increase observed in the Southern African light commercial vehicles [1].

Loss Of Function Of The Additives

Most additives are sacrificial in nature [8] and typically degradation of the functions of detergency, acid neutralisation and anti-wear additives can be expected to occur as the lubricant is exposed to increased quantities of contaminants over an extended period of time [7][9]. Surprisingly, despite high levels of fuel sulphur, Total Base Number (TBN) depletion was relatively limited during this investigation with the lubricants having adequate TBN reserve at a stage when the lubricant was rendered unsuitable for further use on the basis of viscosity increase.

Oil Consumption

There are two processes through which engine oil is consumed. Firstly, evaporation of the lighter fractions in the oil (vapour phase consumption), and secondly the liquid consumption of the oil during engine operation (liquid phase consumption). Evaporation of the lighter fractions plays a role in increasing the viscosity, as only the higher viscosity, heavier fractions remain in the oil. Conversely, the result of oil consumption is that the remaining used oil is diluted and enhanced with fresh oil [10][16].

ENGINE OIL DEGRADATION IN SOUTHERN AFRICA

Oil analyses have illustrated that the oil drain interval is dictated by a relatively rapid increase in lubricant viscosity. In extreme cases, gelling of the lubricant has led to lubrication breakdown and catastrophic engine failure during cold starting in various engine types. This rapid increase in viscosity has been the result of oil sludging which is thought to be accelerated by the following factors [1]:

Vehicle Work Load

Vehicle Loading

Although the legal limit for loading of these vehicles is 1 ton, vehicles are often overloaded, which leads to extended operation at extreme engine load and maximum fuelling, causing high soot production and the presence of large amounts of unburned fuel in the engine.

High Speed Driving

Due to the long distances that are travelled in Southern Africa, vehicles are operated at high speeds with maximum fuelling for a large proportion of the travelling time. Diesel injection pumps are often up-rated so as to deliver more power. This causes the engine to overfuel and produce an excessive amount of soot and unburned fuel. The resulting higher operating temperatures accordingly also lead to a higher rate of oxidation of the oil.

Ambient Conditions

Operation At High Altitude

Large portions of the major commercial regions of Southern Africa are at altitudes in excess of 1 300 m, where the air density is approximately 13 % lower than that at sea level. If an altitude compensation device has not been fitted to the diesel pump, or if the pump is not adjusted accordingly, overfuelling will occur.

Atmospheric Conditions

Air density is much more sensitive to temperature changes than diesel density. At high ambient and under-bonnet temperatures, which are common in Southern Africa, less air will be drawn into the combustion chamber for an approximately constant amount of diesel delivered. This has essentially the same effects as operating at high altitude. High ambient temperatures also lead to an increase in the combustion chamber temperatures, resulting in higher oil temperatures and a higher rate of oxidation of the oil.

Dust Content Of The Air

Due to the higher dust content of the intake air in typical South African driving conditions, standard Japanese and European air filtration systems are often not suitable for local use. The amount of air that is drawn into the engine will be reduced as the air filter becomes blocked, leading to overfueling. The problem of dust is illustrated by the fact that many locally operated vehicles are equipped with high capacity air filtration systems.

Southern African Fuel Properties

Heavy Fractions

South African diesel tends to have a higher density and final boiling point than Japanese and European diesels. Consequently local diesel generates more smoke and soot than would be the case in Japan or Europe. A comparison of South African and Japanese diesel specifications has been made in Table 1.

Table 1. Comparison of South African & Japanese diesel specifications [11].

	Typical Density [kg/l]	Typical 90 % Point	Typical End Point
South Africa	0.837 - 0.857	~360 °C (spec. = 362 max.)	~390 °C
Japan	0.8337	~334 °C (spec. = 350 max.)	~358 °C

Sulphur Content

The current SABS (South African Bureau for Standards) standard specification for locally marketed diesel fuel allows for a maximum sulphur content of 0.55 % by mass [12]. At this stage of the research no significant evidence had been found regarding the influence of sulphur on the rate of the lubricant viscosity increase in small diesel engines under South African conditions. There is some evidence that sulphur increases smoke production which in turn could accelerate sludge formation [13]. However, it is generally accepted that a high sulphur content diesel leads to the formation of acid in the engine oil which can deplete the ability of the lubricant to neutralise acids [3]. This issue is addressed at a later stage in this document.

During combustion a large amount of water vapour (approximately 10 wt% of the exhaust gases) is formed, some of which makes its way to the crankcase with the blowby gases. When the temperature in the crankcase drops to below approximately 55 °C, condensation takes place and this water is emulsified by the oil. The sulphur in the engine oil, which is also deposited in the engine oil through blowby (in the form of a sulphur oxides), reacts with the water forming sulphuric acid. This acid causes a reduction in the TBN of the engine oil, and consequent attack of the metal surfaces in the engine block and increase in engine wear [2]. Although the limited oil drain interval in South Africa is normally attributed to the sulphur content of the diesel, indications are that the sulphur content may influence the rate of increase in the viscosity of the oil, but there are other contributing factors aggravating the excessive degradation of the oil.

The Cetane Number And Aromatic Content Of Fuel

The SABS diesel specification [12] requires a cetane number of above 45 while the typical cetane number of diesel fuel is approximately 50. During refining of diesel from crude-oil, the aromatic content, which has a low ignition quality, is reduced to maximise the cetane number of the diesel [14]. However, it is not economically feasible to remove all the aromatics. The aromatic content of the fuel is thought to also play a role in the oil's viscosity increase.

LABORATORY TESTS

Test Cycle

Due to the unique combination of conditions in South Africa, it was decided to develop an appropriate engine dynamometer test cycle. The cycle had to be representative of South African conditions, while it also had to represent the most extreme condition that could be expected on the road. In addition, in order to enable the comparison of a variety of engine oils, reproducibility of the tests was of utmost importance.

Tests were undertaken on a Mitsubishi (L200) 2.5 litre diesel delivery vehicle. The vehicle was loaded with a one ton cement block and driven under various conditions, while the engine oil temperature was monitored. The aim of these measurements was to determine how the oil temperature was affected by different driving conditions. It was found that the temperature of the oil was strongly related to a combination of the engine speed, torque and the amount of fuel injected.

The test vehicle was then instrumented to gather data for the test cycle. Among the parameters measured, were engine speed, coolant outlet temperature, vehicle speed, vehicle distance travelled, oil temperature, exhaust temperature, fuel consumption and inlet air temperature. Engine operation was measured during four different driving conditions namely: (i) low speed, high load operation (at approximately 2 000 rev/min), (ii) high speed, high load operation (at approximately 4 200 rev/min), (iii) high load operation at varying speed and (iv) urban, stop-start driving. The urban driving was based on the urban cycle prescribed by SABS [15]. The measured data was then combined to form the engine dynamometer test cycle, which consisted of 388 steps over 30 minutes, as depicted in Figure 1. A summary of the cycle can be seen in Table 2.

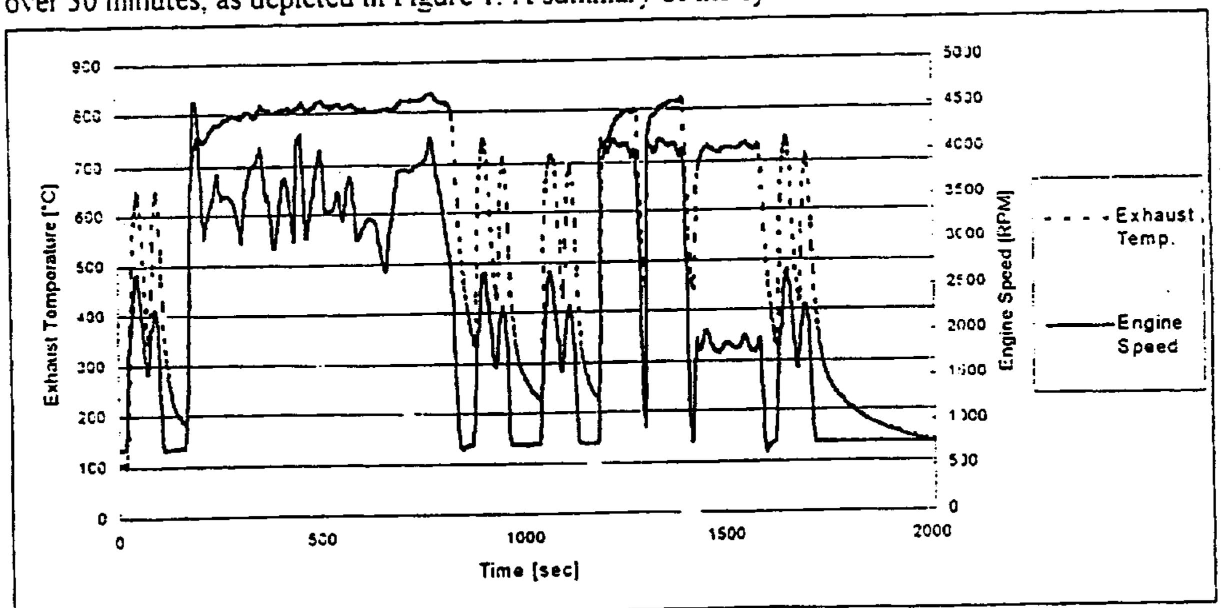

Figure 1. Exhaust temperature & engine speed measured during the engine dynamometer test cycle.

Table 2. A summary of the engine dynamometer test cycle.

Cycle	Time [sec]
Idling	20
Urban	150
High load, varying speed	600
Urban	300
High load, high speed	200
High load, low speed	160
Urban	150
Idling	290
Total cycle time	**30 minutes**

The fact that a diesel engine cools down very rapidly under light load is used in this test cycle to increase the soot formation in the engine. When the engine load is removed, the piston crowns tend to contract, which increases the clearance between the pistons and the cylinder liner and disturbs the operation of the piston rings. If the load is then increased, high blowby rates occur, until the piston crowns and rings regain their equilibrium conditions, as can be seen in Figures 2 & 3. The high blowby resulting from load transitions is thought to accelerate oil sludging and viscosity increase.

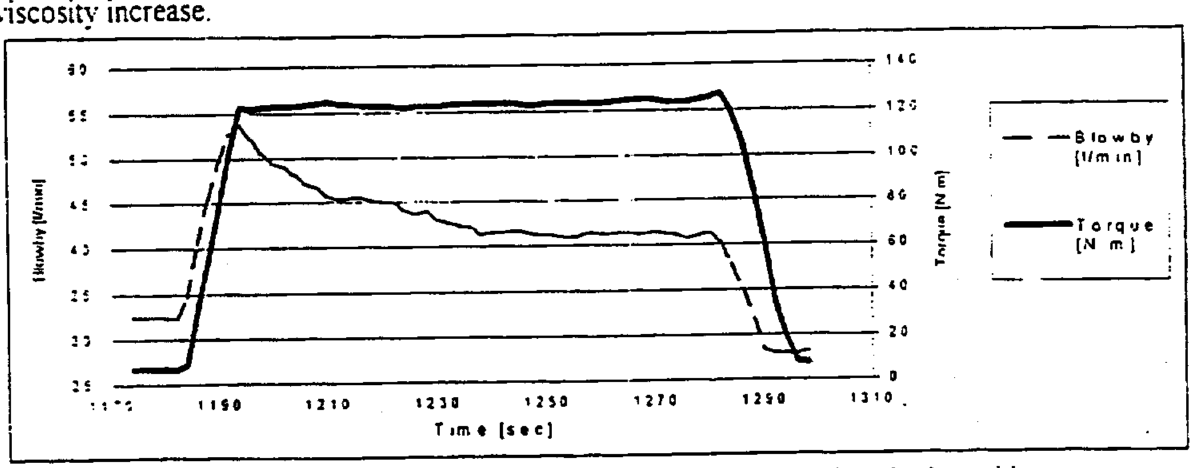

Figure 2. Measured torque and blowby illustrating high blowby after a load transition.

Throughout the test cycle, idling and the urban cycle stages are used to cool the engine down. The main purpose of the high speed, varying load cycle was to oxidise the oil. A lot of soot would also form during this part of the cycle, because the engine is operating at maximum fuelling. When the engine idles at the end of the cycle, the valves controlling the flow of the cooling water to the engine oil and engine coolant heat exchangers were fully opened, to ensure maximum oil cooling. During this step the engine coolant temperature dropped to 54°C and the engine oil to 79°C (it normally operated at temperatures of up to 125°C). After this cool down period the cycle was restarted at step 1.

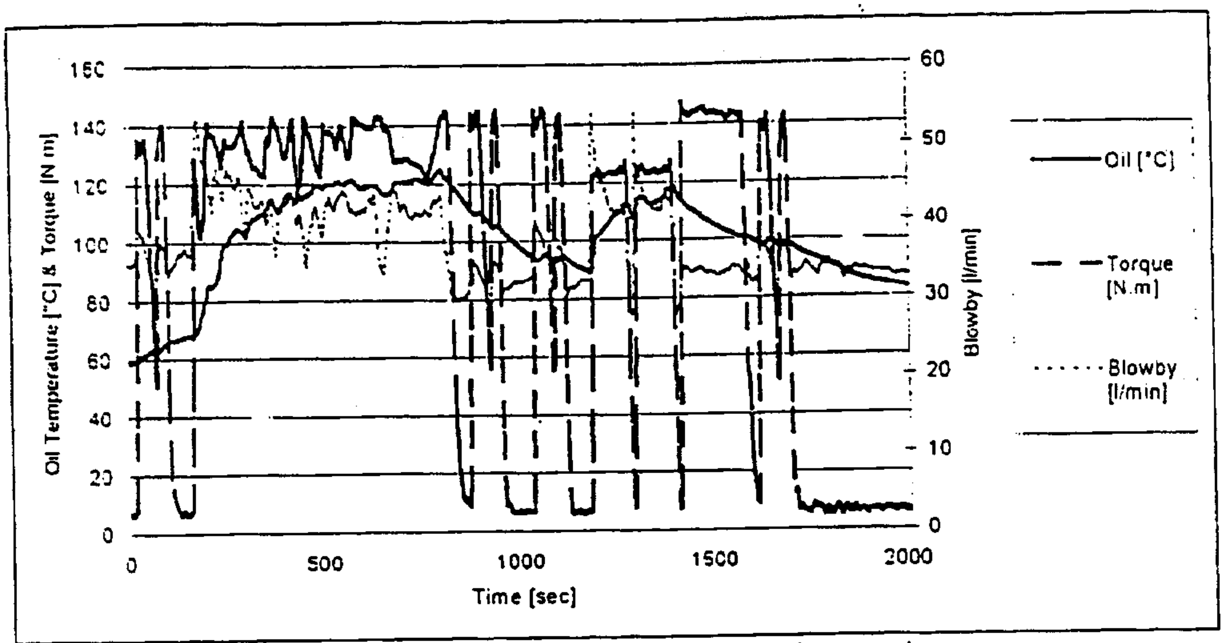

Figure 3. Engine parameters measured during the test cycle.

The total equivalent distance travelled during a 30 minute cycle was 26,5 km and the equivalent fuel consumption based on this distance was 21,1 litres per 100 kilometres, which exceeds actual road conditions indicating that the test cycle was an extreme and accelerated test.

Lubricant Evaluation

The engine was run for a total of 940 hours on the above cycle; testing 6 different oils. While the engine ran unmanned for most of the time, oil samples (100 ml) were taken every 25 hours. Oil A was used in the first and third tests, to determine repeatability of the tests, while different oils were used in the second and subsequent tests. This procedure was essential, to confirm the reproducibility and ability of the cycle to differentiate between a good oil and ones that were less suitable for the application. The order and duration of the tests is displayed in Table 3:

Table 3. A summary of the test oils used in the engine during the laboratory tests.

Test	Test oil	SAE	API	Test	Viscosity at 40 °C	TBN[1]
1	Oil A	-30	CF	100h	97.1	17
2	Reference oil A	15W-40	CE	51h30	105.7	10.8
3	Oil A	-30	CF	149h	97.1	17
4	Oil B	-30	CF	131h30	98.7	15
5	Oil D	15W-40	CF	150h	119.8	15.2
6	Oil E	15W-40	CG-4	120h	131.0	10.1

[1] According to ASTM D2896 [mgKOH/g of Oil]

Oil consumption was monitored on the basis of top up requirement to the nearest 100 ml during the tests. At this stage it should be mentioned that the oils that required to be topped up more regularly had an advantage over the other oils, since they received a fresh charge of oil during the test. The top up volume of all the oils is displayed in Figure 4.

Discussion of the Engine Dynamometer Test Results

The rate of increase in viscosity was used to differentiate between the different test oils. The wear metal concentrations, which are normally an indication of engine wear rate and often indicate degradation of the oil, consistently confirmed that the engine's condition was stable throughout the tests.

When analysing the results, it is important to keep in mind that the engine oil capacity of the test engine was approximately 500 ml more than that of the standard engine. This was because the oil was cooled with an oil to water heat exchanger, which slightly increased the engine's oil capacity

When evaluating a lubricant, a few factors should be considered. Firstly, the rate of increase in the viscosity should be as low as possible throughout the test. Secondly, at no stage during the test should there be any significant increase in the rate of viscosity increase, since this could indicate breakdown of the oil or total loss of one of the additive functions. Finally, wear metal content should under no circumstances deviate from the established trends. A sudden rise in the rate of oil thickening has been observed to correspond with a dramatic rise in the wear metals, thus justifying the use of viscosity as the criteria for lubricant replacement in this application.

The acceptance criteria presented in Table 4 have been proposed for determining the suitability of the lubricants for use in light commercial diesel applications. These criteria are also presented graphically in Figures 4, 5, 7, 8 & 9.

Table 4. Proposed acceptance criteria for the engine oil.

Duration	Viscosity @ 40 °C
100 hrs / 14 000 km	< 200 [mm^2/sec]
125 hrs / 17 500km	< 250 [mm^2/sec]
50 hrs / 7 000 km	Increase by max. 40 % of initial viscosity
100 hrs / 14 000 km	Increase by max.100 % of initial viscosity

The results in Figure 4 indicate that of all the oils that were tested during this investigation, the Oil A was consistently the most resistant to viscosity increase.

An interesting observation was that the monograde oils tended to perform relatively well when compared to the multigrade oils with similar additive packages. This difference was initially attributed to the loss of volatile fractions from the multigrade oils which was limited in the monograde oils. Although the possibility of soot and insolubles interacting with the viscosity index improver (VII) of the multigrade oils was identified.

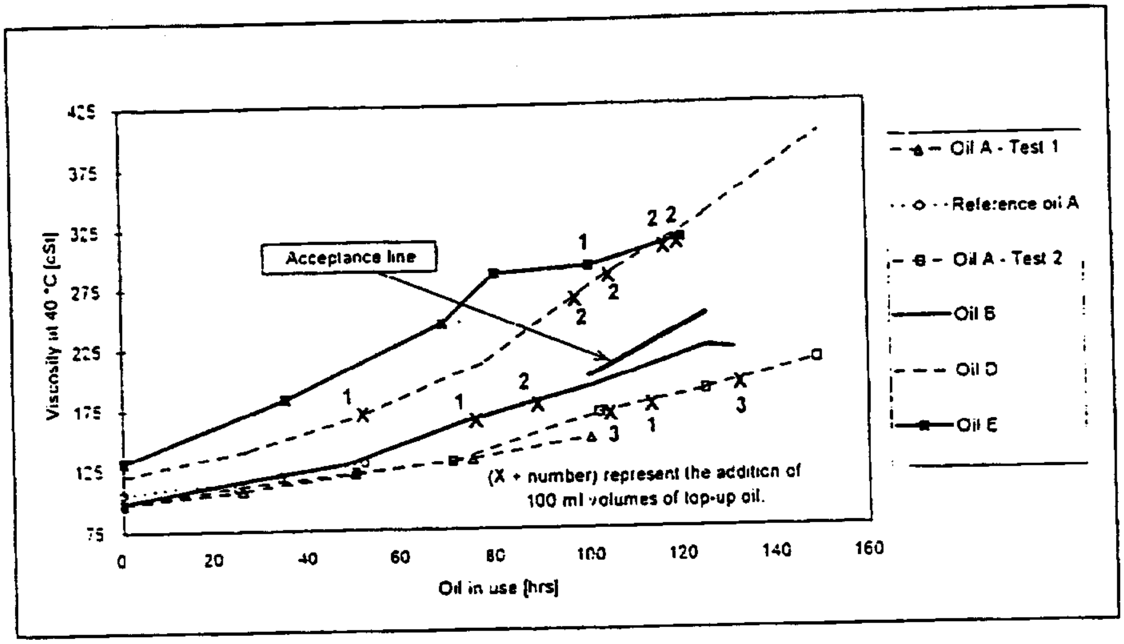

Figure 4. Results from oils tested on the engine dynamometer test cycle.

This suggested that the combination of the base oil and the additive package plays an important role in resisting the viscosity increase.

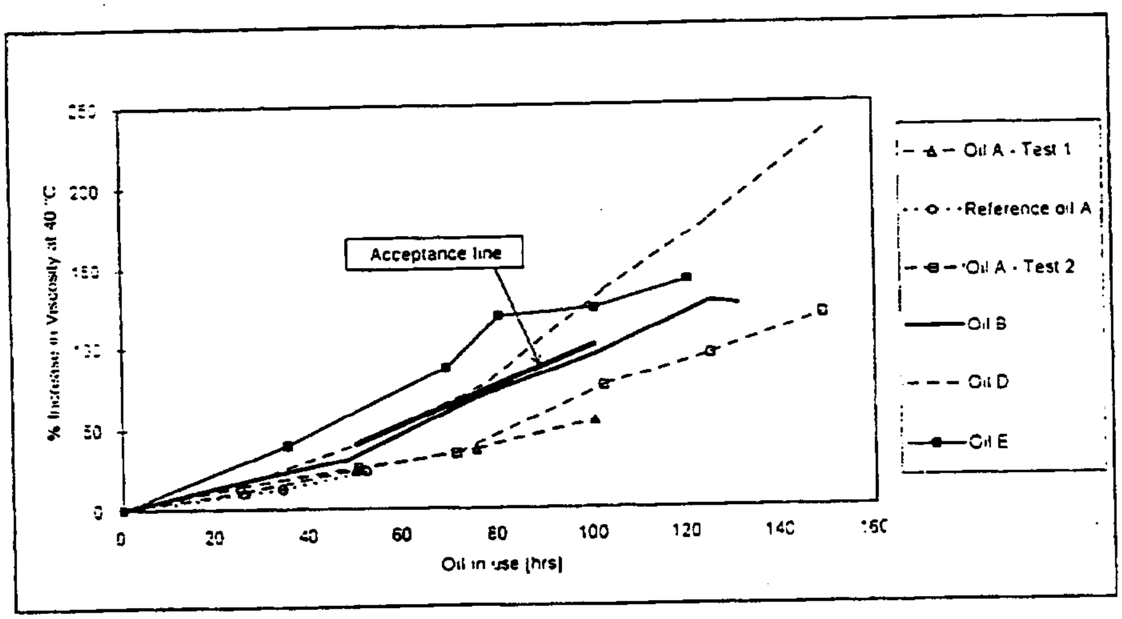

Figure 5. The viscosity increase of the oil expressed as a percentage of initial viscosity.

ROAD TESTS

A vehicle fleet was identified in which the vehicles were operated under closely controlled conditions. Load conditions were severe, yet consistent and maintenance and fuelling of the vehicles was closely controlled. A number of additional vehicles were also identified with significantly different and less severe duty cycles. A total of eight vehicles were used for the road tests in which ten oils were evaluated. Diesel injection pumps on all the vehicles were calibrated prior to the commencement of the road tests.

Test Vehicle Preparation And Test Control

All the vehicles that were tested were marked, to prevent interference with the test vehicles. Before the test oil was put into a test vehicle, the used engine oil was drained and the engine was flushed with the test oil. The vehicle was driven for approximately 10 kilometres with the flush oil. after which it was drained and discarded. After this the vehicle was refilled with the test oil, which was sampled at 2 500 km intervals [17].

Although six of the vehicles received their diesel from the same source, their results could not be compared directly. This was due to differences in driving styles and engine conditions and a variation in the work load of the different vehicles. These differences were eliminated by testing one oil in a variety of vehicles and comparing the results. By doing this it was found that there was a strong relationship between fuel consumption (which was influenced by engine calibration, vehicle load and driving style) and the rate of the degradation of the oil. This relationship is clearly illustrated in Figure 6.

Vehicle 1 was a delivery vehicle that was used for light load deliveries, mainly in town, but also to nearby towns. The rest of the vehicles were all part of a fleet of vehicles delivering newsprint to nearby towns (loads ranging from 500 kg to above 1 ton). The furthest town was 80 kilometres distant along a highway.

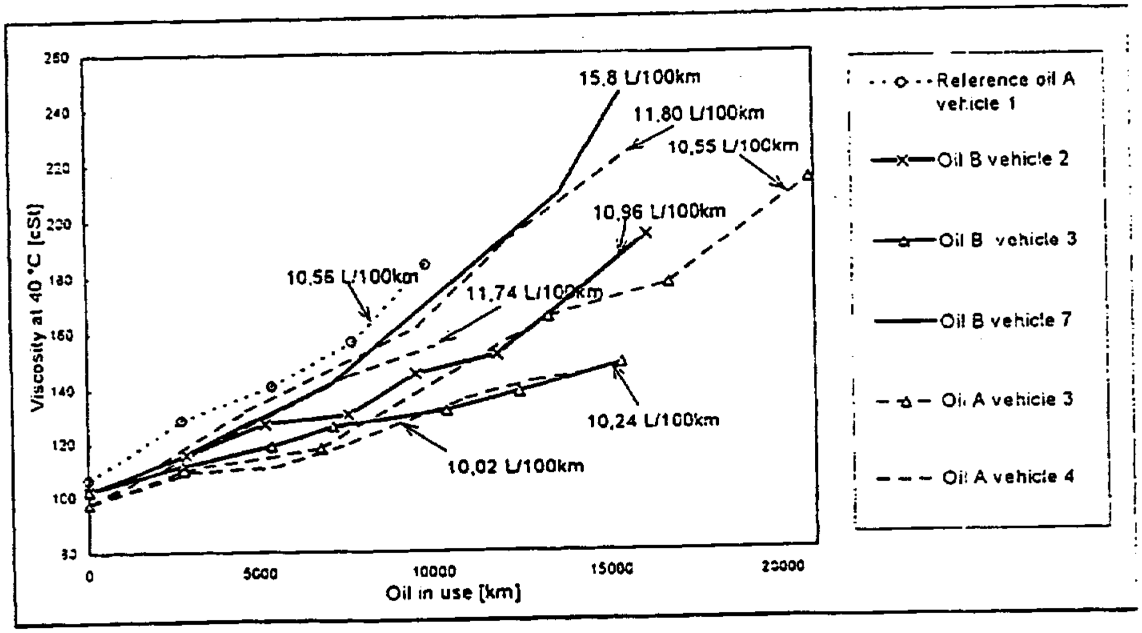

Figure 6. The relationship between oil degradation and fuel consumption.

Discussion of the Road Test Results

Although the fuel consumption of the vehicle in which Reference oil A was tested, was relatively low, indicating a light workload, the rate of degradation of the oil was high. This was because the oil was not as suitable for use in this application as the other oils that were tested. All the other results confirmed the strong relationship between fuel consumption and the rate of degradation of the oil. Two different oils were tested repeatedly in order to determine a relationship between the conditions of the different vehicles. These two oils were Oil A & B. Table 5 lists all the oils that were included in the road tests:

Table 5. A summary of the test oils used in the engine during the road tests.

Test oil	SAE Viscosity Grade	API Category	Viscosity at 40 °C [mm²/sec]	TBN
Reference A	15W-40	CE	106.4	10.7
Reference B	20W-50	CF	149.4	10.5
Reference C	20W-60	CD	217.5	12.7
Reference D	-30	CC	106.5	6.4
Oil A	-30	CF	97.1	17
Oil B	-30	CF	98.7	15
Oil C	10W-40	CF	90.0	15
Oil D	15W-40	CF	119.8	15
Oil E	15W-40	CG-4	131.0	10.1

The effect of the condition of the fuel injectors in the IDI engine on the oil degradation was investigated. Injectors were replaced after a vehicle had completed 106 000 km. The results of these tests, before and after injector replacement, and the multiple tests on the same oil are presented in Figures 7 & 8. Despite the fact that the injectors were found to be badly worn, causing improper atomisation, their replacement did not significantly affect the rate of viscosity increase. This result would indicate that IDI engines are not as sensitive to injector condition as would be expected from DI engines. It was thus concluded that all the observed differences in the results were due to the variance in work load of the vehicle and most specifically fuel consumption.

The results show that Oil A was suitable for use up to 15 000 km and the wear metal trends showed that normal lubrication functions were maintained beyond this point Since these vehicles were operated under typically severe Southern African conditions (except for the fact that they were tested at sea level), it was concluded that it would be safe at this stage to advise a 7 500 km oil drain interval. This recommendation only applies to vehicles equipped with an altitude compensation device to reduce engine fuelling with reduced atmospheric pressure.

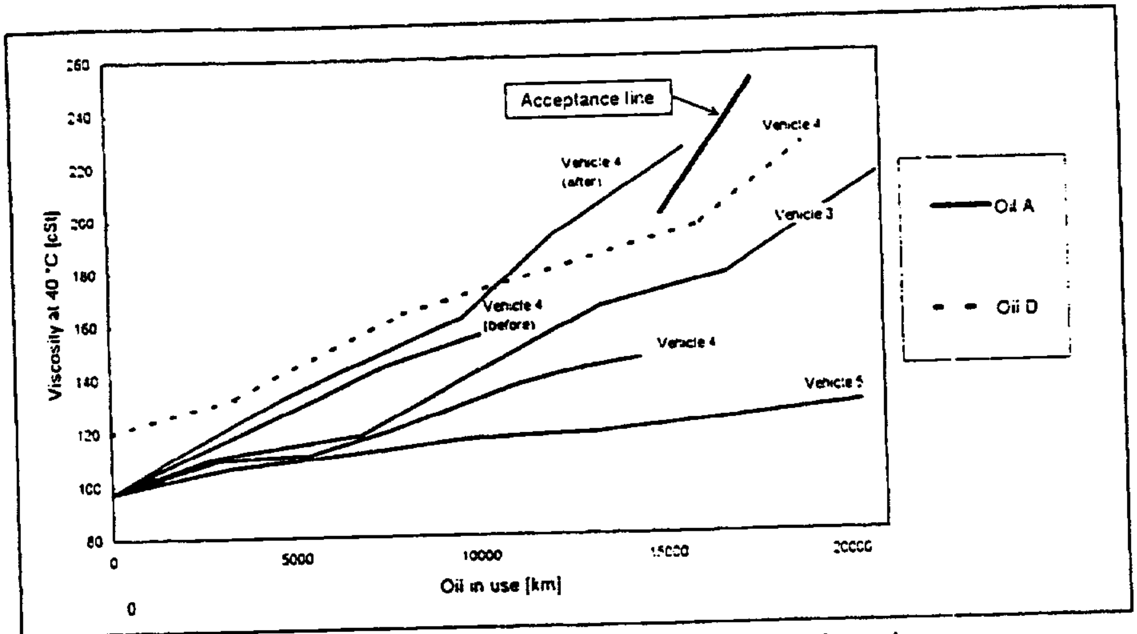

Figure 7. Oil degradation of Oil A & D measured during the road tests

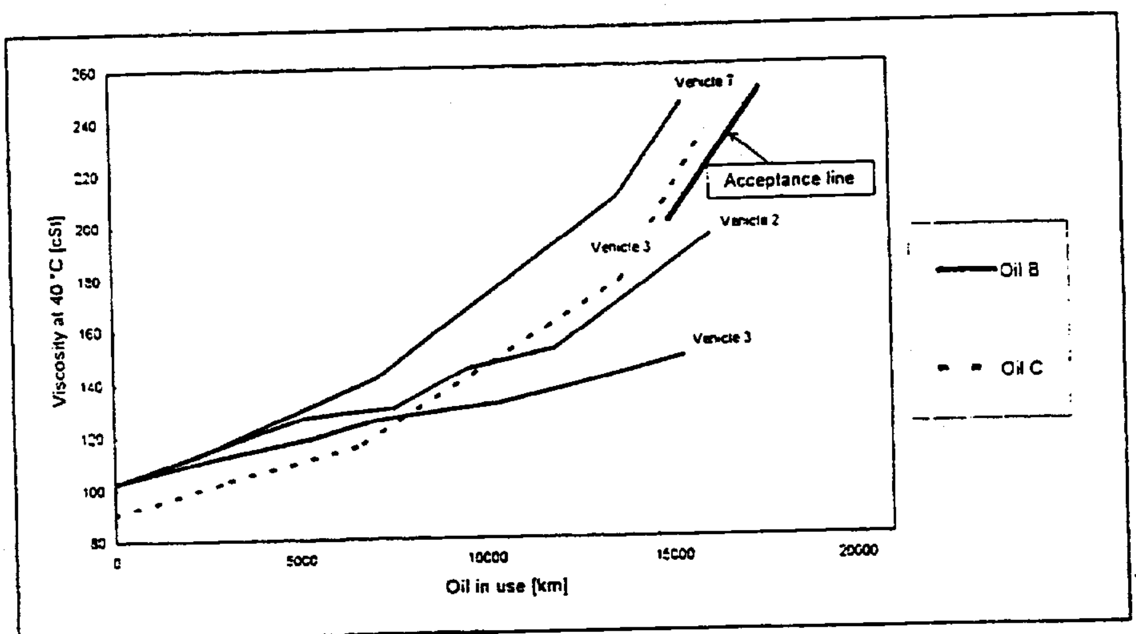

Figure 8. Oil degradation of Oil B & C measured during the road tests.

The road test results also confirmed the observation that the monograde oils experienced lower rates of degradation than the multigrade oils. This indicated that multigrade oils should not be encouraged for use in diesel engined, light commercial, Japanese vehicles in Southern Africa. Indications are that a monograde lubricant with high sulphated ash and TBN should be sufficient. Significant fleet costs saving could thus be achieved by using an appropriate monograde oil over an extended oil drain interval of 7 500 km. Figures 9 & 10 summarise trends in the viscosity and iron concentration.

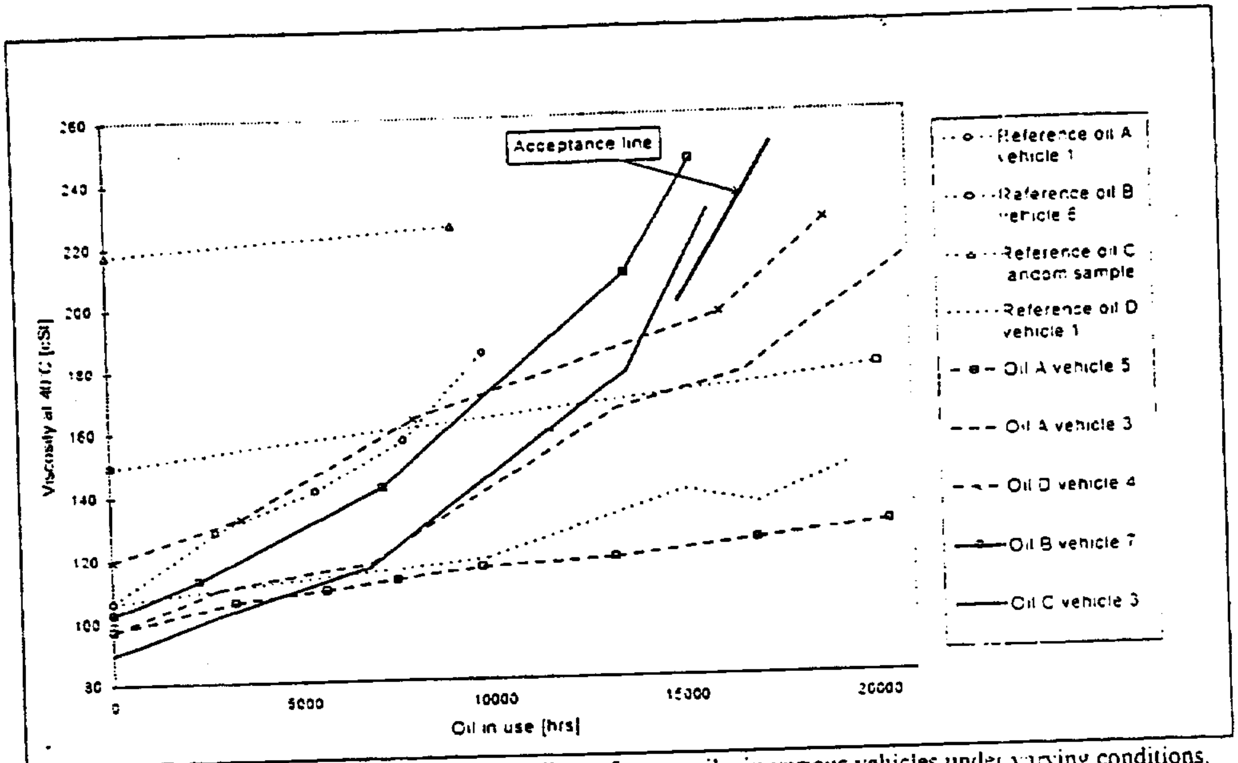

Figure 9. Test results from the road tests, including reference oils, in various vehicles under varying conditions.

The constant rate of increase of the wear metal, depicted in Figure 10, indicated that engine wear was within acceptable limits during all the road tests. The reduction in the rate at which the wear metals increased in some cases was most likely as a result of top-up oil that was added.

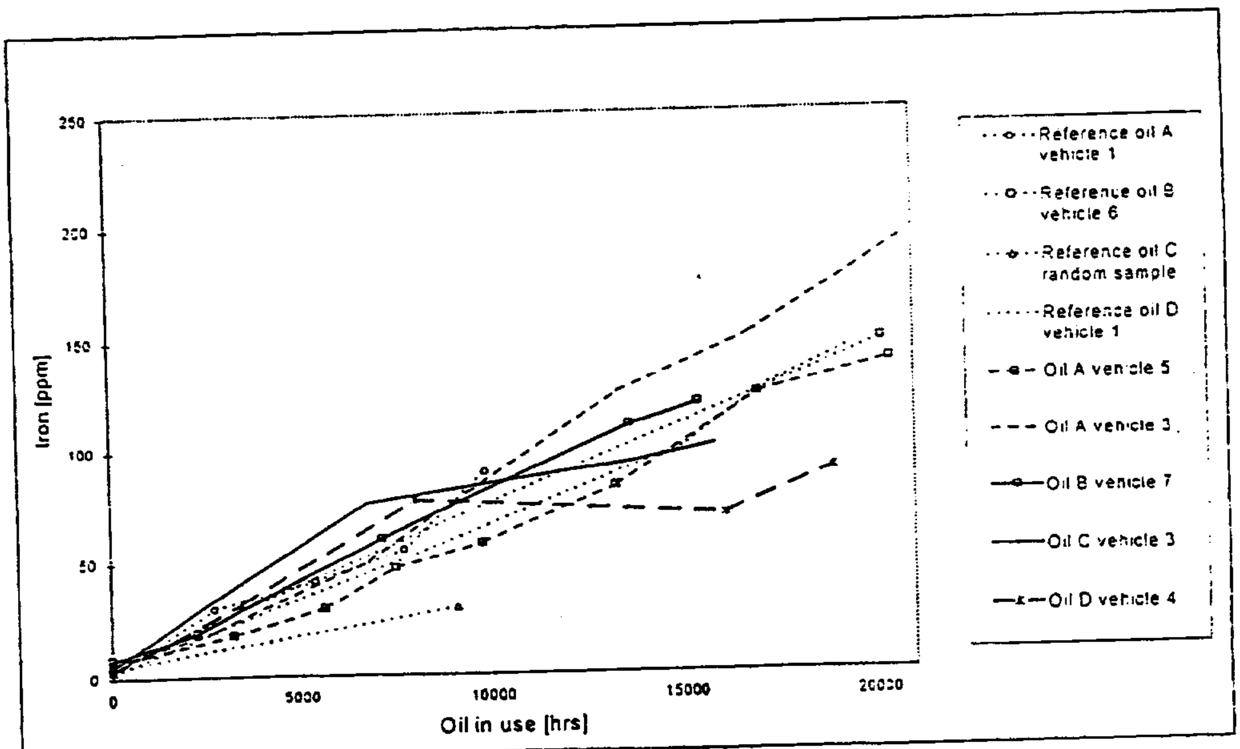

Figure 10. Iron metal levels measured in the test oils during the road tests.

SENSITIVITY OF LUBRICANT DEGRADATION TO FUEL PROPERTIES

In order to evaluate the sensitivity of lubricant degradation to fuel properties tests were carried out in which only the fuel was changed between tests. From experience gathered during the laboratory and road tests, a significant influence of fuel properties on the lubricant life became evident. This led to the commencement of the next phase of the study: investigating the influence of fuel properties on the lubricant's life. The goal of the study was to give an indication of the extent of influence of the fuel properties and not to perform an accurate analysis.

In principle, this test was very similar to the previous tests performed in the laboratory, with the main difference being that the fuel was changed from test to test, while the lubricant remained the same. The engine was run on the same cycle as before, using one of the lubricants that were evaluated in the previous series of tests. [18]

Test Fuels

The first test fuel was a normal crude-oil derived diesel, while the second fuel was synthetic diesel produced by Mossgas. The main difference between the fuels was firstly the difference in sulphur levels, and secondly the difference in fuel density. The aromatic content of the Mossgas diesel is also relatively low compared to typical crude-oil derived fuel. The detail of the two fuels can be seen in Table 6.

Table 6. A summary of the test fuels

Test Fuel Properties			
Property	Unit	Mossgas Synthetic Diesel	Crude-oil Derived Diesel (CDD)
Density @ 20 °C	kg/l	0.8052	0.8558
Distillation Recovery			
90%	°C	322	358
Final Boiling Point	°C	363.2	387
Kinematic Viscosity @ 40 °C	mm^2/s	2.68	4.061
Total Sulphur	% (m/m)	< 0.001	0.46
Carbon Residue	mass %	0.06	0.08

Influence of Fuel Properties on Engine Performance

There are various differences in the above fuels that would influence the operation of the engine. Testing was done to identify and confirm these changes in engine operation:

- The decreased fuel density of the Mossgas diesel resulted in less fuel being delivered to the engine, since the fuel delivery of these specific pumps is volume based. This would have the same effect as de-rating the fuel pump.
- The reduced final boiling point of the Mossgas diesel ensures more complete combustion, reducing the amount of smoke produced in the engine.
- The reduced kinematic viscosity of the Mossgas diesel will also influence the delivery of the pump.
- The higher levels of sulphur is known to increase the corrosive attack on the engine. From the tests performed it also seems likely to have an effect on the quality of combustion, as well as the amount of smoke produced in the engine. [13]

The above statements are confirmed by the following graphs:

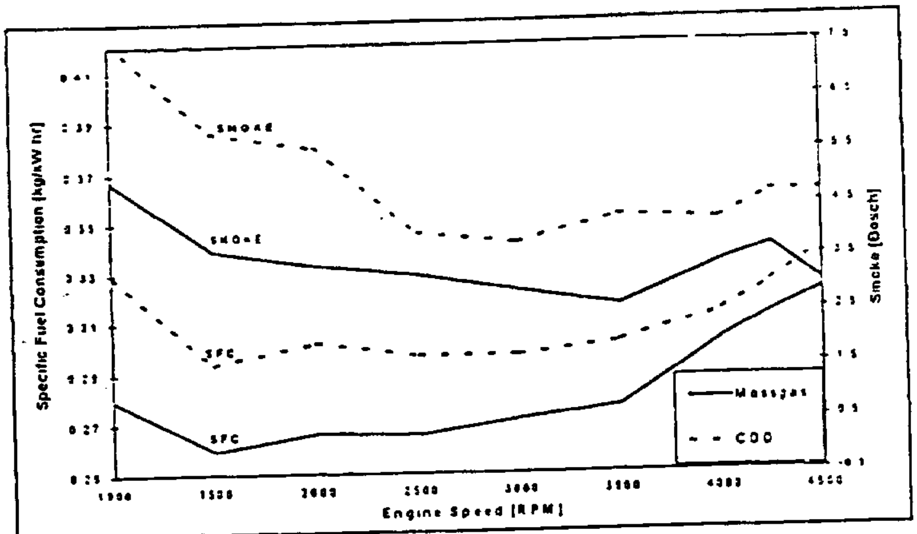

Figure 9. Smoke and SFC measured at maximum fueling for the different fuels.

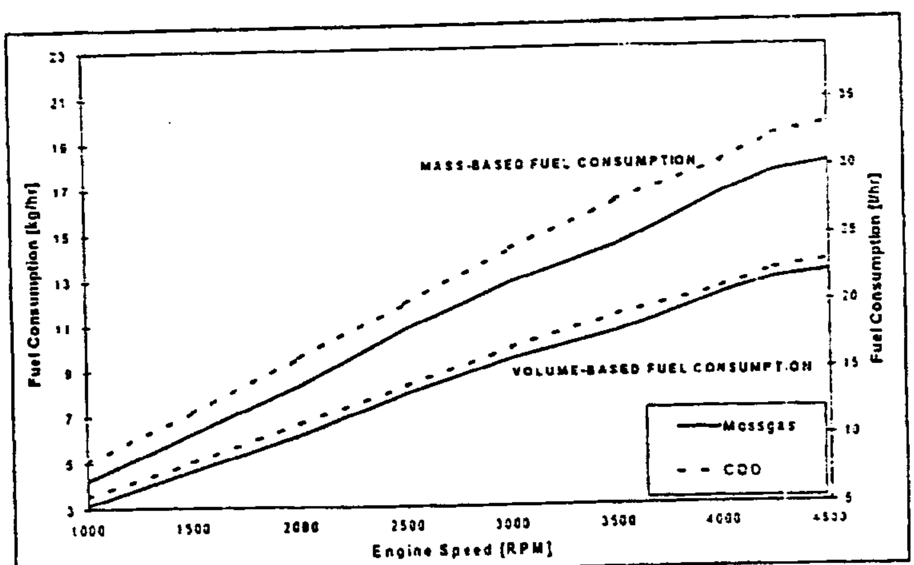

Figure 10. Mass and volume-based fuel consumption of the different fuels.

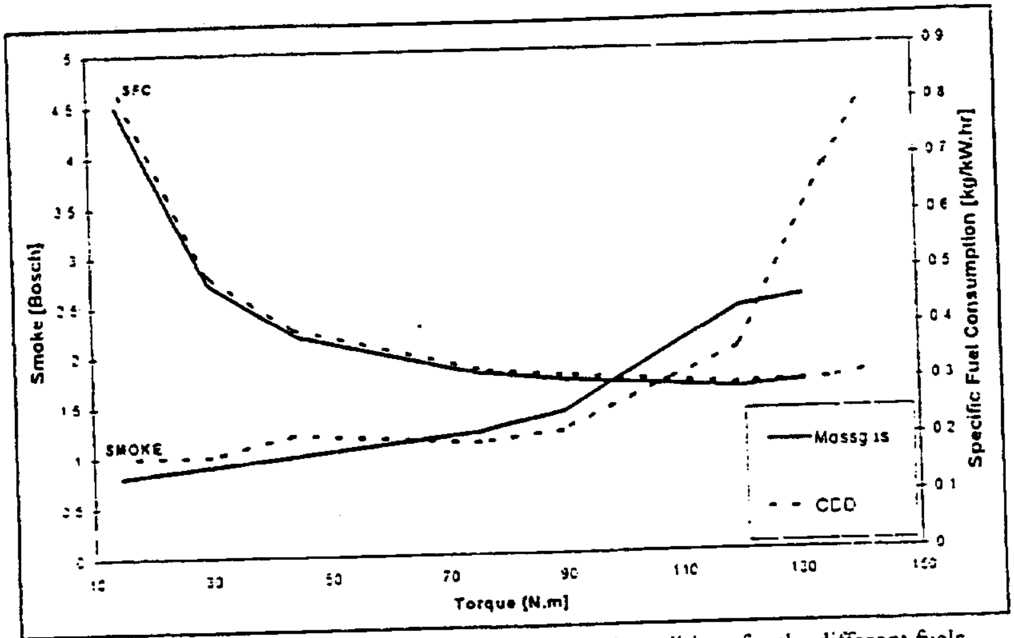

Figure 11. Smoke and SFC measured at part-load conditions for the different fuels

Discussion of the Fuel Property Test Results

Figure 12 illustrates the viscosity increase that resulted with the two different test fuels. These results indicate that fuel properties have a very significant effect on the problem of viscosity increase. It is also evident that the lubricant and its additive concentration has a marked effect on the rate of viscosity increase. When looking at the results, it is evident that the difference in fuel properties has a substantial influence on the rate of viscosity increase of the lubricant, thus justifying further attention. [18].

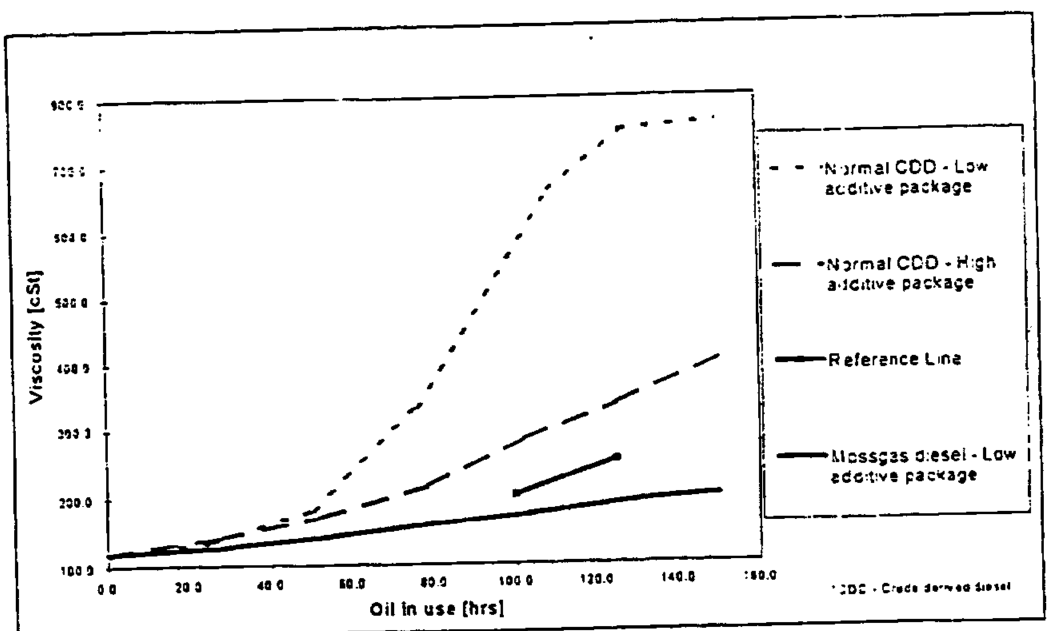

Figure 12. Rate of lubricant viscosity increase measured for the different fuels.

CONCLUSIONS AND RECOMMENDATIONS

This investigation confirmed that the predominant reason for the limited oil drain interval was rapid viscosity increase as a result of sludging. Where it were not for the increased viscosity and combustion related contaminants, the lubricants would generally be fit for further use. While oxidation did contribute to the sludging process, soot contamination was the dominant cause of the rapid viscosity increase. During the course of the investigation it also became apparent that the limited oil drain interval was responsible for excessive downtime, while severe engine damage as a result of oil sludging is a significant problem in the field. A unique combination of local conditions were found to be responsible for the abnormal rate of the viscosity increase.

From this investigation it can be concluded that the oil drain interval of the Mitsubishi 4D56 engine could be safely extended by 50 percent from 5000 km to 7500 km, as long as a proven oil is used and the vehicle was equipped with an altitude compensation device, if it is required to operate at high altitudes. This would not only reduce maintenance costs and downtime, but there would also be a reduction in the amount of oil requiring disposal.

It was observed that the monograde oils consistently outperformed the multigrade oils with similar additive packages. This difference was partly attributed to the loss of the lighter fractions from the multigrade oils, while other mechanisms, possibly related to the viscosity index improvers (VII), are thought to also play a role in this problem.

On the basis of the road test results it is strongly recommended that where possible, oil drain intervals should be based on total fuel consumption. If fleet owners have a system in place to monitor the fuel consumption, these records should be used to indicate the need for draining the engine oil. The length of the oil drain intervals would thus not be determined by the distance travelled, but by the amount of fuel that has been consumed by the engine, thus automatically taking the vehicle's work load into account.

It was also found that fuel properties, such as fuel density and sulphur and aromatic content, do have a considerable influence on the rate of degradation of the engine oil and accordingly on the extent of oil drain intervals. The magnitude of the effect of fuel properties on oil degradation is adequate to justify considerable further investigation. The increased cost of revised fuel specifications may well be justified by a reduction in total vehicle operating cost.

In summary, the cause and mechanism of oil degradation has been identified, suitable lubricants to combat the problem have been found and a reliable maintenance strategy has been recommended. If implemented these recommendations have the potential to significantly reduce vehicle maintenance cost.

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